Structural Response and Resulting Quantity-Distance Debris Collection Techniques and Results

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Introduction

One of the important factors in citing protective aircraft shelters (PAS) is the quantity of explosives that can safely be stored inside a PAS. The maximum amount of explosives depends upon the distance to other inhabited facilities and the distribution of peak overpressures and debris which might result from an accidental detonation of the stored explosives. Experimental data provides the basis for calculation of minimum separation distance between explosive stored and other types of base facilities. These separation distance are referred to as explosives quantity-distance (Q-D) criteria and are normally specified as scaled ranges form the source of the explosion.

A new aircraft shelter designed by the Norwegians is under construction in Norway and will be used by NATO forces. The front door and other structural details of this shelter differ significantly from the US Third Generation design. These differences have raised questions regarding the applicability of the Q-D criteria derived from previous test programs. The Norwegian and US government entered a Memorandum of Understanding to address these concerns. The test program included the construction of four 1/3 scale structural models of the PAS. These models were subjected to internal detonations of various weights of high explosives. This paper will discuss response of the shelter and associated debris.

Test Structure and Model

The test structure was a 1/3rd scale model of the Norwegian/US PAS design. The structure is illustrated in figure 1. The Norwegian/US design is similar to the US Third Generation PAS design, but differs significantly in the door and structural details. The door is one piece made to two steel plates with a stiffeners between the two plates. The arch and rear wall have the same type of shape but there is about three times the steel in the Norwegian/US design.

The reinforced concrete shelter was analyzed using the finite element code DYNA3D run on a SUN workstation. An elastic-plastic material model was used. The assumed material properties are given in table 1. The yield strength was determined by assuming a steel ratio of .027, and assuming a

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1992**	2. REPORT TYPE	3. DATES COVERED **00-00-1992 to 00-00-1992**

4. TITLE AND SUBTITLE **Structural Response and Resulting Quantity-Distance Debris Collection Techniques and Results**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Phillips Laboratory/WSB, ,Kirtland AFB,NM,87117**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA260985, Volume II. Minutes of the Twenty-Fifth Explosives Safety Seminar Held in Anaheim, CA on 18-20 August 1992.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**41**	

TABLE 1. ASSUMED MATERIAL PROPERTIES	
Parameter	Reinforced Concrete
Young's Modulus (gPa)	30.0
Poisson's Ratio	0.2
Density (kg/cu.m.)	2403
Yield Strength (mPa)	3.7
Hardening Modulus	0.0
Hardening Parameter	0.5

yield strength of the reinforcing bars and steel line of 60000 psi. Figure 1 shows a schematic of the assumed cross section of the shell. The pressure time history used were generated by GUSH3D and actual data. The pressures used for the three tests are shown in figure 2 for the various areas.

Quantity-Distance Program Plan

In an attempt to fully document and characterize the Q-D response of the 1/3rd scale US/Norwegian aircraft shelter, an extensive debris collection program and free-field overpressure measurement plan was generated. Four methods were used to collect debris data: Four, 5 degree collection sectors were defined, which emanated from GZ. All fragments remaining within these sectors post test were collected and thoroughly documented. A 360 degree survey of large debris was made, which was used to determine symmetry of the structure breakup. Fragment collection packs were used to collect debris, and help determine areal densities in the vertical plane. High speed photography was used to record initial velocities of large discernable fragments, or to track photo poles attached to them. Free field gages, both passive and active were located throughout the test bed, which were used to determine the 1.0 psi (6.89 kpa) contour.

The following is a list of debris collection requirements for the 1/3rd scale US/Norwegian aircraft shelter tests. Parameters are based on TO-11A-1-47[1], study of the Distant Runner[3] (DR) full scale, and 1/10th scale test programs. Collections zones, methods, dimensions, and the like, meet or exceed TO requirements and parallel DR research so that comparisons, if possible, can be made between the two shelter types. It is believed that enough similarities exist between the arch's of these two shelters that useful data or generalized information can be gained from this comparison

Fragment Parameters

Minimum collectable fragment dimensions are based on results from DR. From DR, it was determined that a minimum fragment mass of 0.3 lbs (136 gm)[3] would bound the lower limit of the 58ft-lb kinetic energy criteria (hazardous fragment for personnel). At 1/3rd scale, the minimum fragment mass is .011 lbs (5.04 gm). These minimum requirements are pertinent only to the 5 degree sectors where all fragments are being collected. Applying this and a reinforced concrete density of 150 lbs/ft^3, yields the following 1/3rd scale minimum criteria:

- Minimum acceptable dimension for collection purposes: That which can be captured by a sieve with a square mesh of 0.50 inch (12.80 mm) separation. Fragments which pass through such a mesh will be ignored.
- Mass: > 0.01 lbs (5.04 grams), which is the mass of a 0.5 inch cube of reinforced concrete.

Table 2 shows sieve sizes used for collecting fragments. Sizes were chosen, based on the TO and 1/10th scale tests, with additional sizes being used to reduce labor requirements for data collection. All sieve sizes are rounded to the nearest industry standard. Relative mass for a cube is also shown in table 2. For the 360 degree survey, initial plans were to limit fragment collection to Those fragments ≥ 5.00 inch (127 mm), which shall be surveyed and labeled in place.

TABLE 2. Sieve Sizes

Mass	Sieve Size (inch:mm)	Scaled Mass (lbs:gm)	Full Scale (lbs:gm)
1	0.500: 12.80	0.011: 4.82	.29: 132.89
2	0.625: 15.87	0.021: 9.61	0.57: 259.55
3	0.750: 19.05	0.036: 16.11	0.99: 448.50
4	0.875: 22.22	0.058: 26.38	1.57: 712.19
5	1.000: 25.40	0.087: 39.37	2.34: 1.63k
6	1.250: 31.75	0.170: 76.90	4.58: 2.08k
7	1.500: 38.10	0.293: 132.89	7.91: 3.59k
8	2.000: 50.80	0.694: 314.99	18.75: 8.50k
9	2.500: 63.50	1.356: 615.22	36.62: 16.61k
10	3.000: 76.20	2.343: 1.06k	63.28: 28.70k
11	4.000: 101.6	5.550: 2.52k	150.00: 68.04k

Areal Distributions: 5° Collection Sectors

Primary fragment collection sectors consist of 5° arcs of length R (figure 3), where R is a function of Net Explosive Weight (NEW), and is then subdivided into segments of length r_0 (16.40 ft (5 m): 49.22 ft at full scale). Sectors emanated from GZ, except sector 4, which is shifted reward so that its center line passes through a rear corner of the arch. Sector 4 does emanate from the longitudinal line parallel to the arch walls, which passes through GZ. The four collection sectors are defined as follows:

Sector 1: Perpendicular to door.
Sector 2: Perpendicular to left side arch (as viewed when facing the front of the shelter).
Sector 3: Perpendicular to rear wall.
Sector 4: 135° from the longitudinal axis passing through the left rear corner of the shelter (as viewed when facing the front of the shelter)

For the first three NEW's scheduled, R was defined by the relationship $75W^{1/3}$ for the first two tests (W is NEW in lbs ($29.75Q^{1/3}$: Q-kg)). For test 3 the sponsor felt that this relationship may not provide sufficient collection area, therefore R was increased to match the DR events 4 and 5's maximum collection ranges. US/Norwegian shelter test 3 represents 90% of the NEW used

in DR event 4, and 20% of DR event 5. R was rounded up to the nearest 10 m increment and was defined, by test, as follows:

test 1: R1 = 164.04 ft (50 m).
test 2: R2 = 229.65 ft (70 m).
test 3: R3 = 656.20 ft (200 m).

For test 3, R3 would have been 328.08 ft (100m), had the original relationship been used. The first sub-sector (r_0) starts at 32.81 ft (10 m) from GZ, which is near the berm's edge, perpendicular to the shelter. Subsequent sectors are spaced at intervals of r_1.

Rectangular Collection Areas For PAS-1 & 2; Zero Q-D Evaluation

In addition to the 5° sectors, the sponsor requested two rectangular regions, providing a collectior area for all manner of fragments within the "zero" Q-D region (that region which is between GZ and r_0). The first region runs the length of the shelter arch and extends from GZ to r_0. The second region runs the width of the arch/front face of the shelter, and extends from the arch/front face to r_0. It is hoped that the collection debris in these regions will help quantify future computer codes/calculations, and better establish methods used to determine debris throw within the "zero" Q-D region.

360° Ground Survey; 180° Collection Sectors

For the 360° survey, fragment recovery was originally limited to a minimum size of 5.00 inch (127 mm). Such fragments were to be surveyed, labeled and recorded individually. But, as will be shown later, this was unrealistic because of the limited number of large fragments.

The 360° survey area was divided into two 180° collection sectors. Sectors were divided into primary and secondary, based on the level of debris recovery effort. Sectors emanated from GZ and extend to R. Minimum collectable fragment size for the primary sector was originally set at 5 inches (127 mm). Minimum fragment size for the secondary sector was originally set to 10 inches (254 mm). All such fragments which fall within these criterion were surveyed in place with respect to range and angle from GZ. The zero degree radial emanated from GZ and extended perpendicularly through the shelter door. Angles are measured positive in the clock-wise direction. A debris map was generated from these surveys.

Fragment Recovery Packs

Fragment Recovery Packs (FRP's) were used to determine areal densities in the vertical plane, without concern for penetration depth or angle. Previous fiberboard recovery packs have proven to be too dense or resilient to allow fragment penetration, preventing effective data collection. Therefore, a new method was used for this series of test. For PAS-1 this consisted of a 55 gallon drum, cut in half, and lined with foam. For the remaining tests, the FRP's were constructed from 4'x8' sheets of plywood, shaped to create traps similar to the drums (figure 4), and were also foamed lined. The intent of these traps was to allow the fragments to impact the foam, limiting secondary breakup, and rebound to the floor of the trap, thereby increasing the number of recovered fragments.

For PAS-1, a single drum has a frontal area of 5.04 ft^2 (($0.47\ m^2$) 1.83 ft w x 2.75 ft h), while the plywood traps, used for the remaining tests, had a frontal area of 21.33 ft^2 (($1.98\ m^2$) 8 ft w x 2.67 ft h (2.44m h x 0.81m w)). FRP's were placed at r_1 and incrementally spaced by r_0, just out-side of the 5° sectors, alternating left and right sides. For PAS-1, FRP's were placed along side the arch, rear wall, and the 135° collection zones. For the remaining tests FRP's were limited to the arch collection radial, due to the number of plywood traps available. Traps were placed at the anticipated 1 psi range and farther. Recovery packs were aligned side-by-side with their front faces perpendicular to GZ. Placed in this manner, recovery packs subtend a solid angle not less than 0.013 steradians[1].

As a special note, the following documents recovery pack placement and numbers, which follows procedures outlined in TO-11A-1-47. The minimum frontal area for traditional full-scale FRP's is 32 ft^2, and 3.55 ft^2 at 1/3rd

scale. The drums used scale up to 5.5 ft w x 8.25 ft h (1.68 m w x 2.51 m h), yielding a full-scale frontal area of 45.4 ft^2 (4.22 m^2). The plywood traps yielded a frontal area of 192 ft^2 (17.83 m^2) at full scale. The minimum number of packs used is the "subtend (of) a solid angle not less than about 0.013 steradian."[1] A steradian is defined as "the total face area of the recovery packs (A) divided by the square of the distance (R) between the test stack and the recovery packs (A/R steradians)." The results of these requirements are in table 3.

Table 3. Number of Required Recovery Packs Basic Equation: A/R=s			
Description	r_0	$r_0 + r_1$	$r_0 + 2 * r_1$
s	0.013	0.013	0.013
A_{fp}	5.04	5.04	5.05
D_{1st}	32.81	49.22	65.62
R	1,076.0	2,422.0	4,306.0
A	13.99	31.49	55.98
A/A_{fp}	2.78	6.25	11.11
# Bins	3	7	12

Initial Velocities

Initial velocity was to be established through three methods, based on high speed photography and digital analyses of the film; digitizing large discernable fragments, photo poles, and metal/sifcon cubes of known size and mass (sifcon is a concrete & metal fiber mix, developed by NMERI). Large discernable fragments are those fragments which can be positively identified from a frame to frame analyses of high speed film images. In some cases fragments on film can be identified with recovered fragments. For the photo poles, twelve were place along the arch, and three on the front door (figures 5 and 6). Twenty five sifcon cubes (17.88 lbs (8.11 kg) and 0.49 ft^3 (150 mm)) were placed on the arch (for PAS-1, aluminum cubes, 2 inches cubed were used: placement is shown in figures 7 and 8, while the remaining tests used sifcon cubes for their traceability on film: placement is shown in figures 9 through 11). All cubes were numbered so that their impact point could be compared with their starting point. The use of sifcon was preferred since it better simulated the density of the arch.

COLOR CODES

The arch was divided into sixteen distinct segments (figure 12), using a combination of dye and colored beads mixed in with the aggregate. Dye colors

change in discrete elements from foundation to arch peak, in horizontal lifts. The beads change colors from front to rear of the shelter in lateral segments. Volume of beads used in the aggregate/reinforced concrete mix did not exceed 1% of the volume of concrete. Exhaust port, backwall, front wingwall, door segments and right half of the arch were left uncolored (natural grey) concrete. The arch color coding is shown in table 4.

Table 4: Arch Color Coding				
Concrete Dye				
Test	Red	Black	Yellow	Green
PAS-1	0° - 35°	35° -45°	45° - 60°	60° - 90°
PAS-2,3,4	10.6°-33.2°	33.2° - 60°	60° - 90°	0° - 10.6°
Pellet Color				
Test	Red	Black	Yellow	Green
PAS-ALL	1st qrt	2nd qrt	3rd qrt	4th qrt

Free Field Pressures

Static overpressure gage placement for PAS-1 through 4 are shown in figure 13, and coordinates are recorded in table 5.

PAS-1 Structural Damage and Response

This test detonated 3.7kg of C4 explosives in the center of the 1/3rd scale structure. The analysis indicated that the peak acceleration would be 1100G's, while the recorded was 1700g's, figure 14 shows a comparison of predicted vs recorded acceleration. The maximum principal stress was found to be 2.8 mpa. Somewhat lower than the yield strength of the material as shown in figure 15. It was anticipated from the analysis that the structure would respond in the elastic regime for the first test and did. The test structure suffered only minor damage in the first test. No cracks were observed in the visible portions of the arch foundation, and there did not appear to be any separation between the top of the arch foundation and the line base channel. In addition, no separation between the concrete of the arch and top of foundation could be detected on the exterior of the structure. There was no discernable outward movement of the arch foundation. The pattern of hairline cracks was observed in the floor slab around the surface GZ. Within these cracks, and construction joints, the floor slab dished downward to 18 mm at GZ.

Table 5. Free Field Gage Coordinates								
	PAS-1		PAS-2		PAS-3		PAS-4	
GAGE	X (m)	Y (m)	X (m)	Y (m)	X (m)	Y (m)	X (m)	Y (m)
701	-3.0	0.0	-5.0	0.0	-9.0	0.0	-9.0	0.0
702	-5.0	0.0	-9.0	0.0	-24.0	0.0	-24.0	0.0
703	-7.0	0.0	-14.0	0.0	-34.0	0.0	-44.0	0.0
704	-9.0	0.0	-24.0	0.0	-44.0	0.0	-74.0	0.0
705	-3.4	8.0	-3.4	8.0	-54.0	0.0	-84.0	0.0
706	-6.2	10.8	-6.2	10.0	-6.2	10.8	-6.2	10.8
707	6.8	8.0	-16.4	21.0	-16.4	21.0	-16.4	21.0
708	6.8	12.0	6.8	8.0	-23.4	28.0	-30.4	35.0
709	17.0	8.0	6.8	12.0	-30.4	35.0	-37.4	42.0
710	19.8	10.8	6.8	16.0	6.8	12.0	6.8	12.0
711	19.0	0.0	6.8	24.0	6.8	40.0	6.8	40.0
712	21.0	0.0	17.0	8.0	6.8	50.0	6.8	50.0
713	23.0	0.0	19.8	0.0	17.0	8.0	19.8	10.8
714	6.8	-8.0	30.0	21.0	19.8	10.8	30.0	21.0
715	6.8	-12.0	18.0	0.0	30.0	21.0	44.0	35.0
716			21.0	0.0	23.0	0.0	23.0	0.0
717			23.0	0.0	37.0	0.0	37.0	0.0
718			37.0	0.0	47.0	0.0	57.0	0.0
719			6.8	-8.0	57.0	0.0	77.0	0.0
720					6.8	-12.0	6.8	-12.0
721					6.8	-50.0	6.8	-40.0
722							6.8	-50.0

In the heavily reinforced portion of the floor slab between the door pit and the rest of floor slab, several hairline cracks were observed running parallel to the axis of the structure. A gap was noted between the floor slab and the back wall. The most dramatic cracking in the structure was found at

the intersection of the parapet and the top of the front walls on both sides of the structure. Although the crack pattern in the parapet seemed quite symmetrical about the centerline, it was judged that there was slightly more cracking and damage at the right side (side without personnel entrance). Figure 16 illustrates the arch hairline cracks that were observed. The structure was determine as structurally sound and reused for PAS-3.

PAS-1 Preliminary Debris Collection Results

Collection zones, radials, FRP locations, ect, are shown in figure 17, for PAS-1. For PAS-1, no fragments were found, either in the 5° sectors, rectangular collection areas, or in the FRPs. In the 360°region two fragments were located, which came from the front door-jam area. Free field data was collected and is summarized in table 6, and figure 18 shows the 1 psi contour.

Table 6. PAS-1 Static Overpressure

Gage	PSI	Gage	PSI	Gage	PSI
701	1.125	706	0.22	711	0.19
702	0.9	707	0.072	712	0.27
703	0.6	708	0.064	713	0.66
704	0.49	709	0.084	714	0.055
705	0.3	710	0.055	715	0.038

PAS-2 Structural Damage and Test Results

This test detonated 11.11 Kg of C4 explosives in the center of 1/3 scale structure. The analysis predicted that the accelerations would be on the order of 2500g's a while the recorded was 4200g's, figure 19 shows a comparison of predicted vs recorded acceleration. The maximum principle stress for the structure was on the order 3.8 MPa, which is at the yield level as shown in figure 20. It was believed the structure was on the verge of failure for this loading condition.

The structure did indeed fail; it split in two pieces. The front two-thirds of the structure was lifted off the foundation and thrust froward 1 m. The door was blown out 30 m in front of the structure. The structure split apart at a splice location. There was severe cracking on the exterior of the shelter as well as the floor slab. The arch-foundation connection failed in tension as the front two thirds of the shelter was lifted off the foundation and moved forward. The arch section remain intact except for the section that landed on the wingwalls as the structure moved forward. Figure 21 illustrates the failure of the structure as well as the splice locations.

PAS-2 Preliminary Debris Collection Results

For PAS-2, which was the third test in this series, was performed on a second, virgin shelter (figure 22 shows the test bed layout and parameters). Very few fragments were collected in this test as in PAS-1. No fragments were found in the FRPs. In this test, structure break-up was very favorable to Q-D issues. It is believed that it can be safely said that the low end NEW for zero Q-D is established with this test. This statement is based on the lack of debris outside the plan view of the arch. The 1 psi contour is shown in figure 23. Table 7 shows static overpressure results (question marks by values indicate unresolved questions about the data point).

Table 7: PAS-2 Static Overpressures

Gage	PSI	Gage	PSI	Gage	PSI
701	1.7	708	0.04	715	0.8
702	0.95	709	0.02?	716	0.51
703	0.55	710	0.02?	717	—
704	—	711	—	718	0.04
705	0.15?	712	0.1?	719	
706	1.15?	713	0.1?		
707		714			

PAS-3 Structural Damage and Test Results

This test detonated 33.33 kg of C4 explosives inside the center of the 1/3rd scale shelter. The analysis predicted maximum accelerations on the order of 4000g's while recorded was 5200g's, as shown in figure 24 a comparison of predicted vs recorded acceleration. The structure was expected to break up with pieces of the structure moving at 40 m/s. The finite element analysis used was successful at predicting the initial acceleration and velocity of the structure. The maximum principal stress was greater than the yield stress. This indicated that the structure would come part during the test. Stress concentration occurred at the bottom of the arch were the finite element model was pinned and at the top of the structure as shown in figure 25. This indicated that the structure would lift off the arch footing foundation since this was considered the weak link in the structure. This was evident post-test, as the rebar in the arch-footing connection showed classic tension failure in the rebar.

The structure had severe damage post test. It broke into seven major sections as shown in figure 26. An inspection of high speed photography

showed that the structure lifted off the foundation before the breakup occurred. It was evident that the arch-footing connection failed in tension. The door was blown out of the structure and had significant yielding.

PAS-3 Preliminary Debris Collection Results

PAS-3 was tested on the first shelter, the same shelter used in PAS-1 (test bed layout is shown in figure 27). The only issues of concern for the use of this structure would be fragment size (smaller), which could also increase the number of fragments, and allow an early release of the door from the arch, thereby relieving the arch of some impulse. But, considering the size of the charge, it was believed that these effects would be small.

Again, the shelter's response is favorable to Q-D issues. Because the arch moved vertically, with very little horizontal motion, debris containment was assured. Rock rubble scatter was due to the vectored velocity component placed on it due to the arch wall slope and vertical motion. Fragments went as far as 98 m, yet tended to be relatively small in size. A rock rubble distribution map is shown in figure 28. The 1 psi contour is shown in figure 29, and overpressures are shown in table 8.

Table 8: PAS-3 Static Overpressures

Gage	PSI	Gage	PSI	Gage	PSI
701	6.93	708	1.32	715	—
702	2.63	709	0.85	716	1.92
703	1.77	710	1.49	717	0.93
704	1.3	711	0.85	718	0.59
705	0.85	712	0.6	719	0.37
706	2.89	713	5.1	720	1.47
707	—	714	1.05	721	0.56

PAS-4 Preliminary Debris Collection Results

PAS-4 was a 100kg charge. Test bed preparation paralleled PAS-3. Again, as in PAS-3, arch break-up moved vertically, limiting debris throw. Results of debris collection is not available at this time, but pressure data is. Table 9 shows overpressures. Figure 29 illustrates the 1 psi contour, while figures 30 and 31 show pressure level comparisons for the four tests performed to date.

Conclusion

Overall, the effects of the added steel in the arch design for this shelter can be seen. The arch has a tendency to remain together longer and in larger pieces, thereby forcing a majority of the hazardous materials and debris to move vertically, and not in the horizontal plane. But, it can not be determined at this time, if any benefits, or additional hazards are created by the use of rock rubble. At this point in time, it is felt that it does not pose any additional threat.

The use of passive foil pressure gages, for each of these tests, has proven to be of little or no benefit. This has been due to the effects of debris. In a majority of the cases, some quantity of small, dust like debris was found trapped behind the foil of the gage. The presence of debris of any kind leaves the foil data suspect, and therefore was not recorded herein. It has become apparent, that in this test environment, where debris is expected, the foil gages perform poorly.

Table 9: PAS-4 Static Overpressures

Gage	PSI	Gage	PSI	Gage	PSI
701	13.34	709	1.088	716	4.279
702	3.916	710	6.092	717	2.103
703	1.668	711	2.139	718	1.233
704	0.870	712	1.595	719	0.711
705	0.725	713	3.597	720	6.817
706	5.656	714	1.233	721	1.886
707	2.103	715	0.761	722	1.523
708	1.197				

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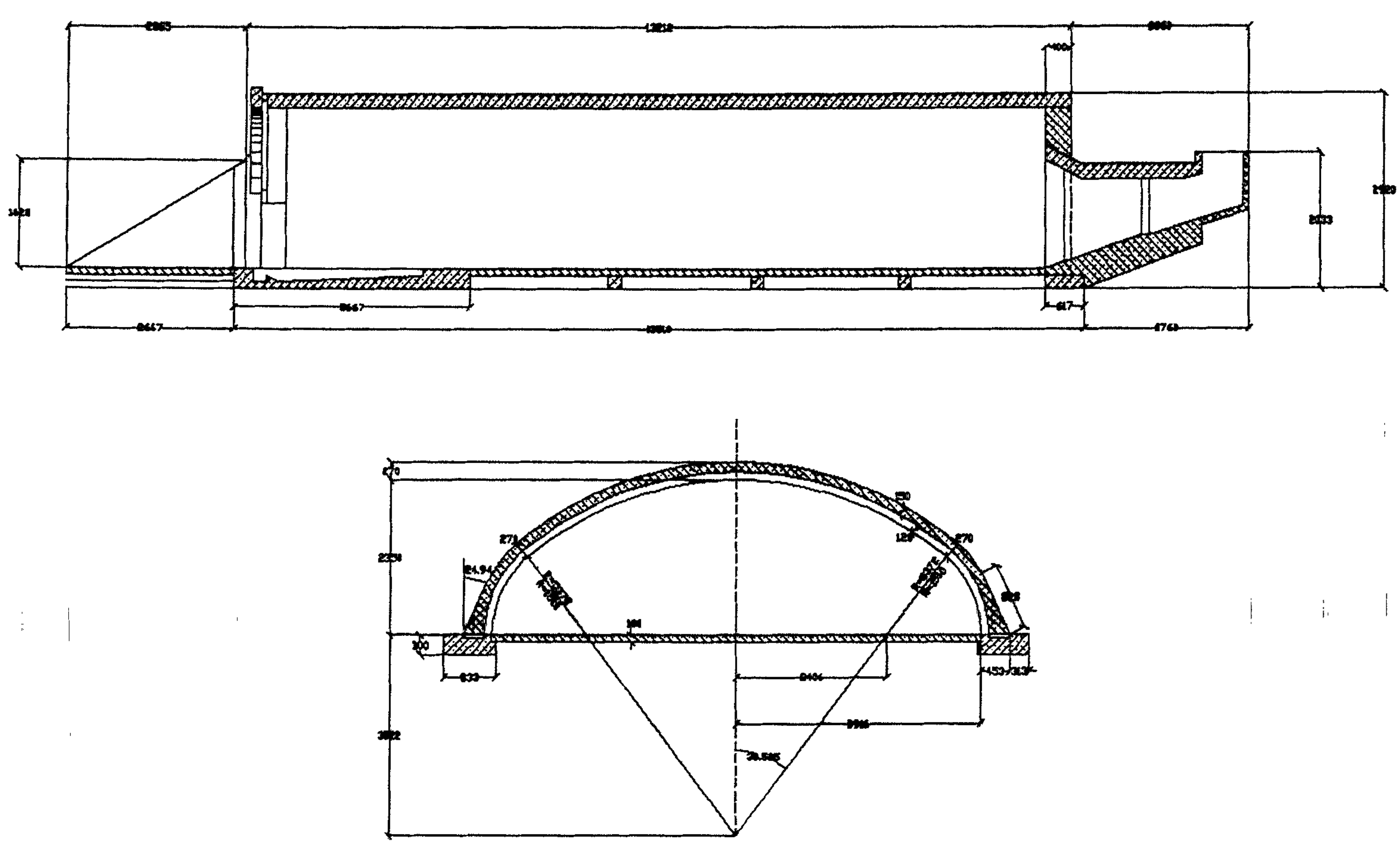

Figure 1. Schematic of Norwegian/US Aircraft Shelter

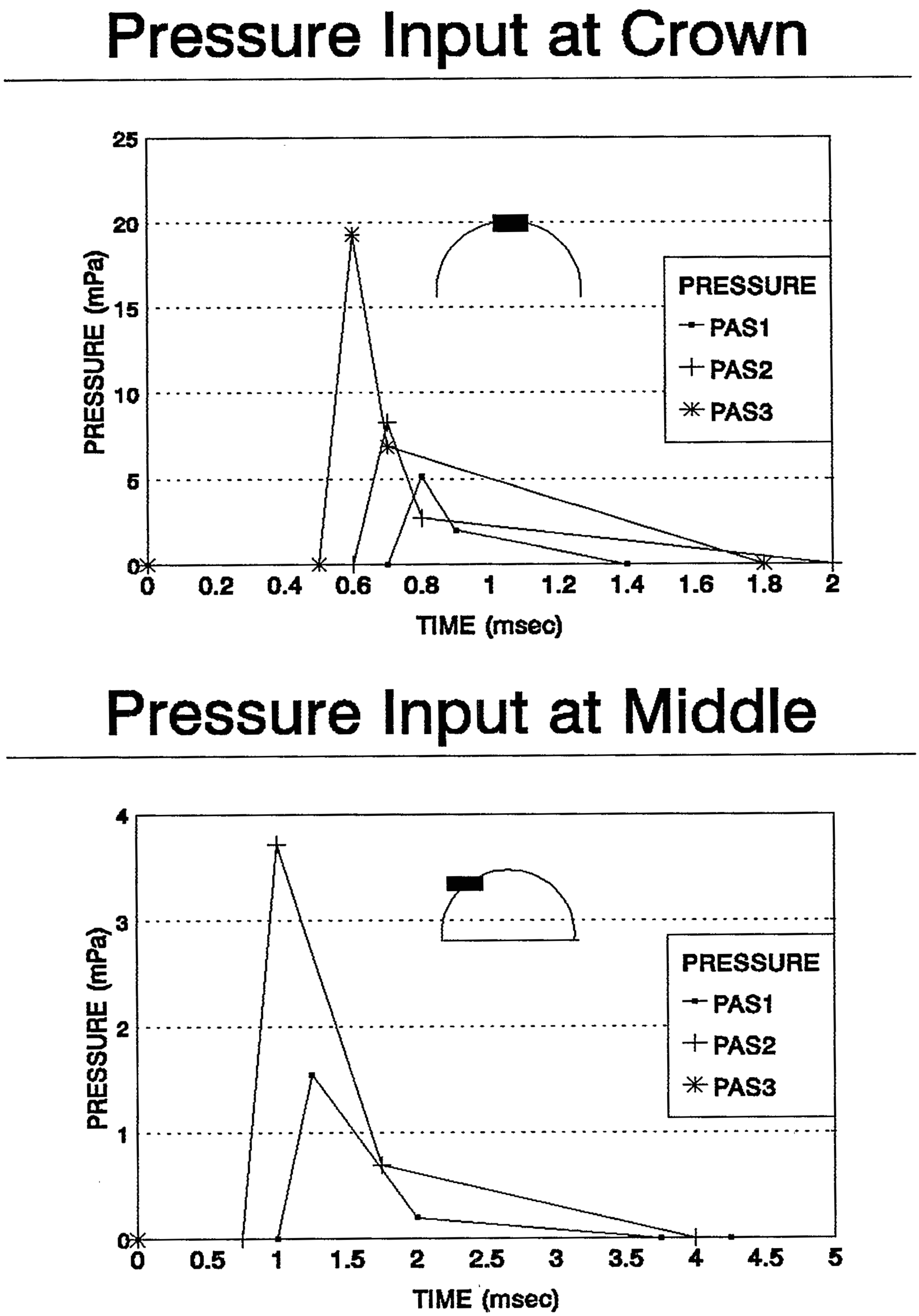

Figure 2. Pressure time histories

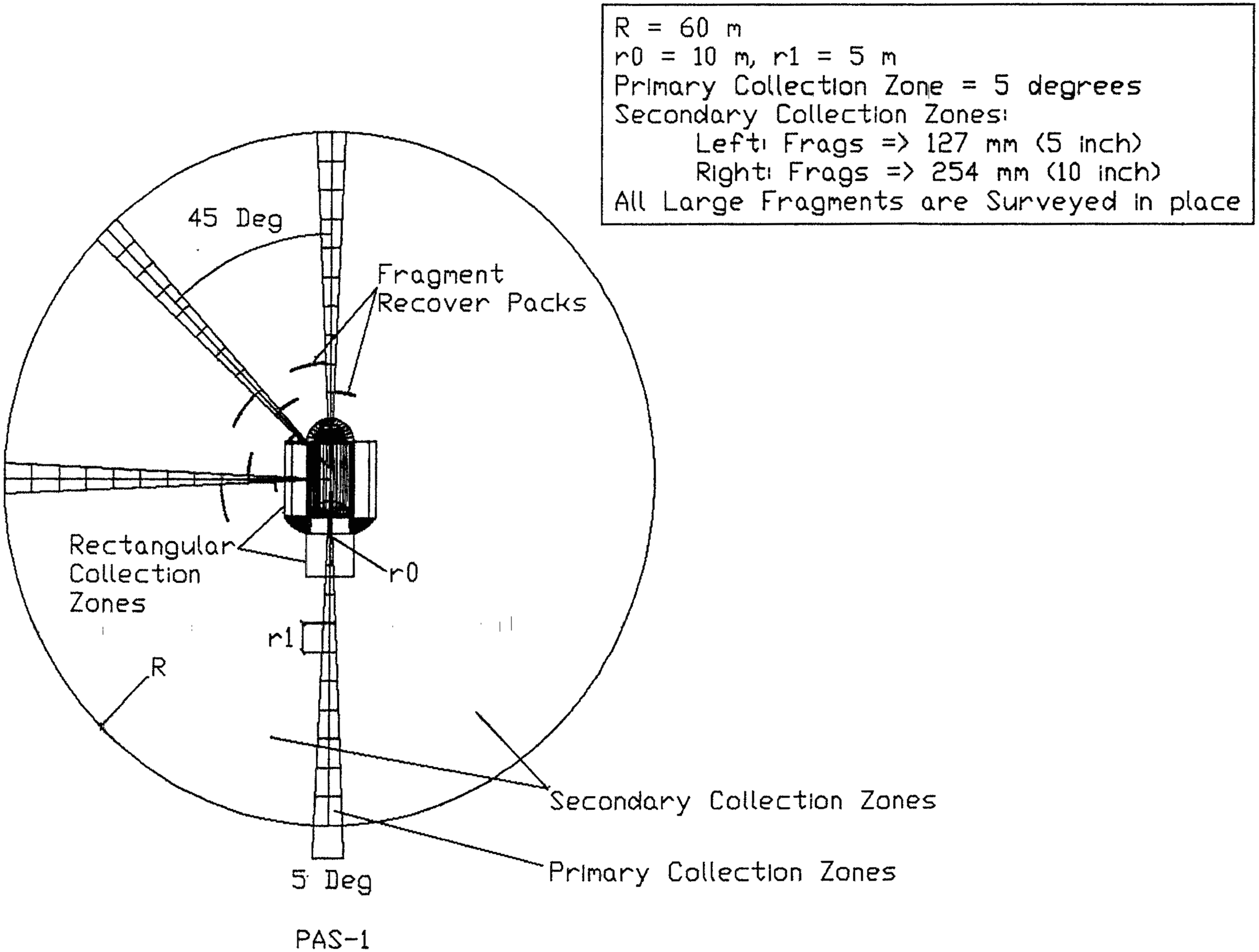

Figure 3: Debris Collection Plan

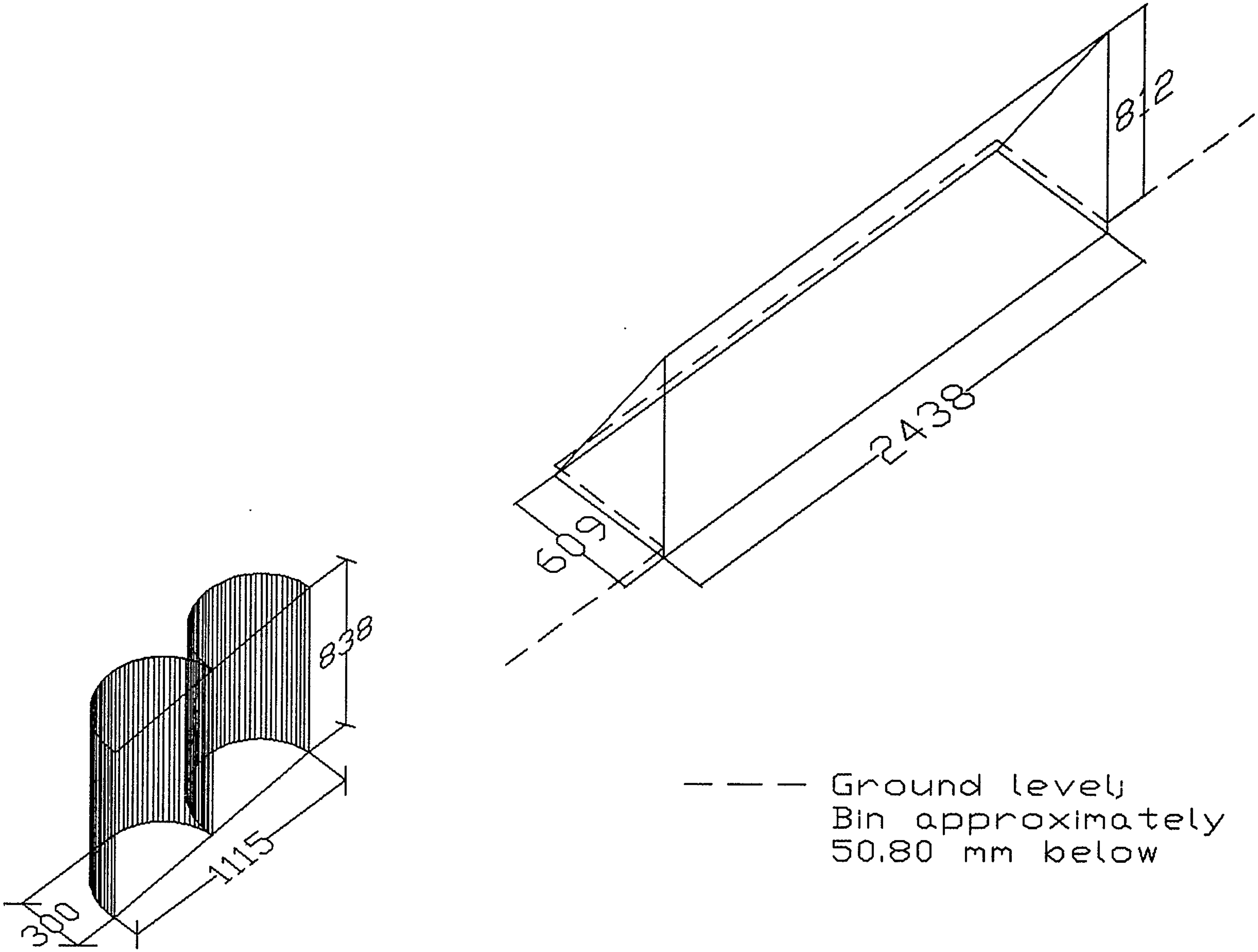

Figure 4: Fragment Recovery Packs

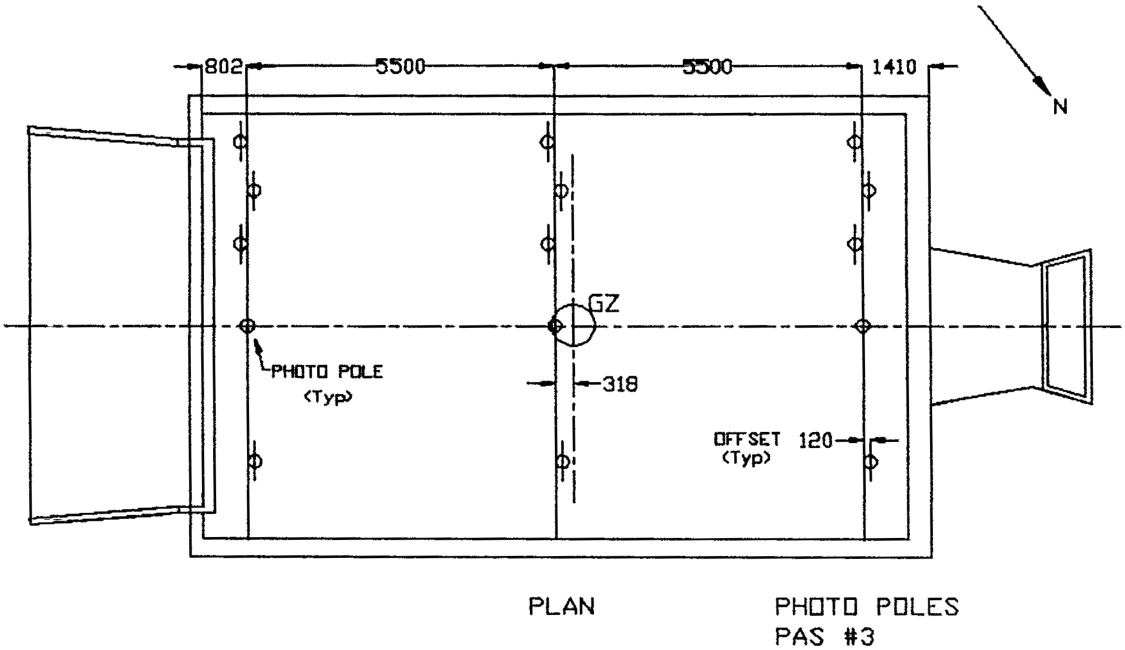

Figure 5: Photo Pole Placement Plan View

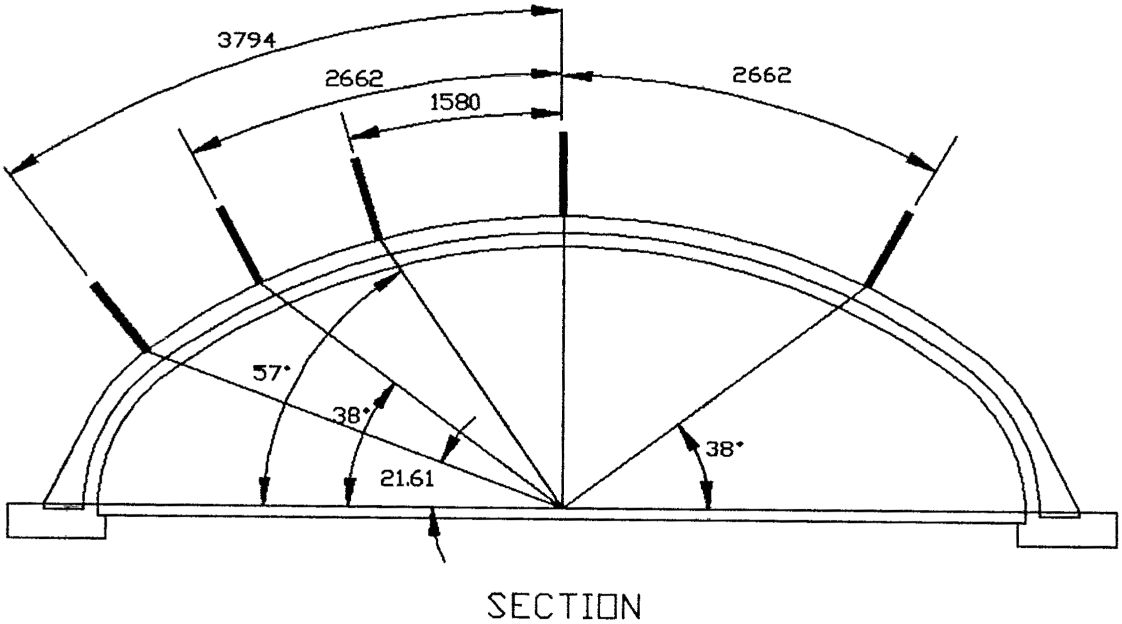

Figure 6: Photo Pole Placement Section View

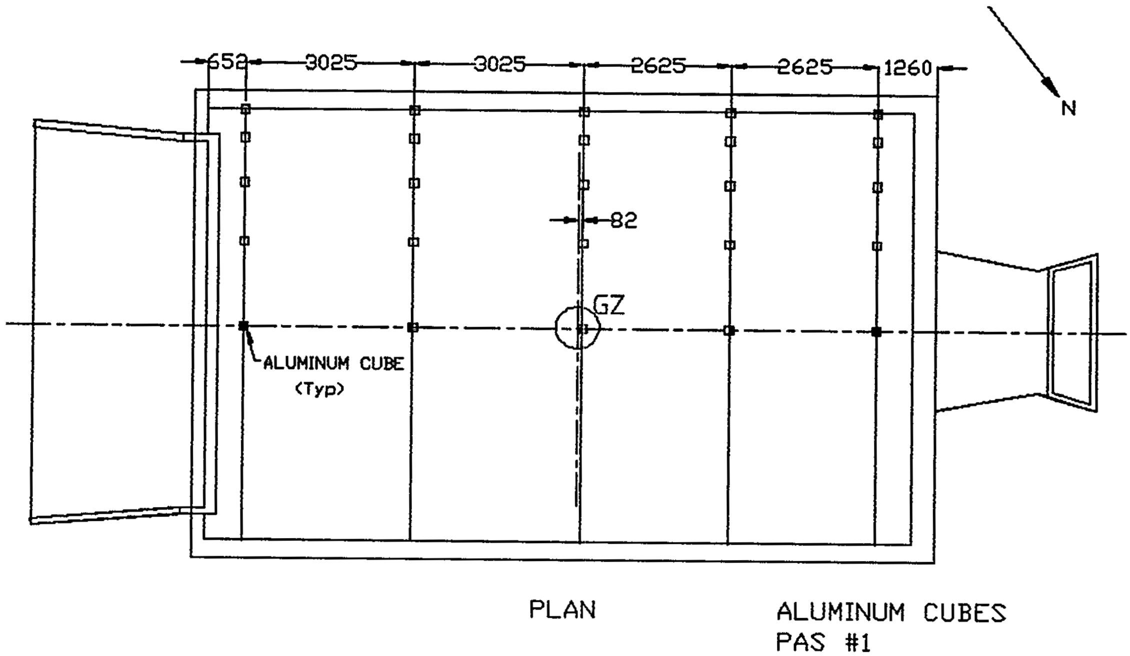

Figure 7: Aluminum Cube Placement Plan View

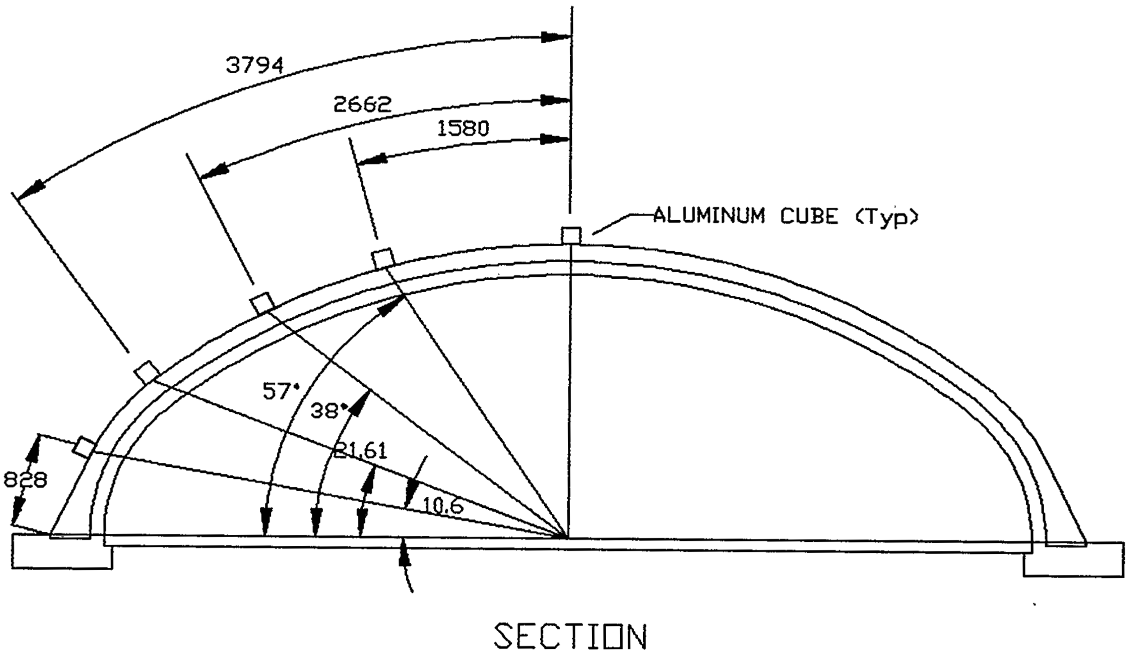

Figure 8: Aluminum Cube Placement Section View

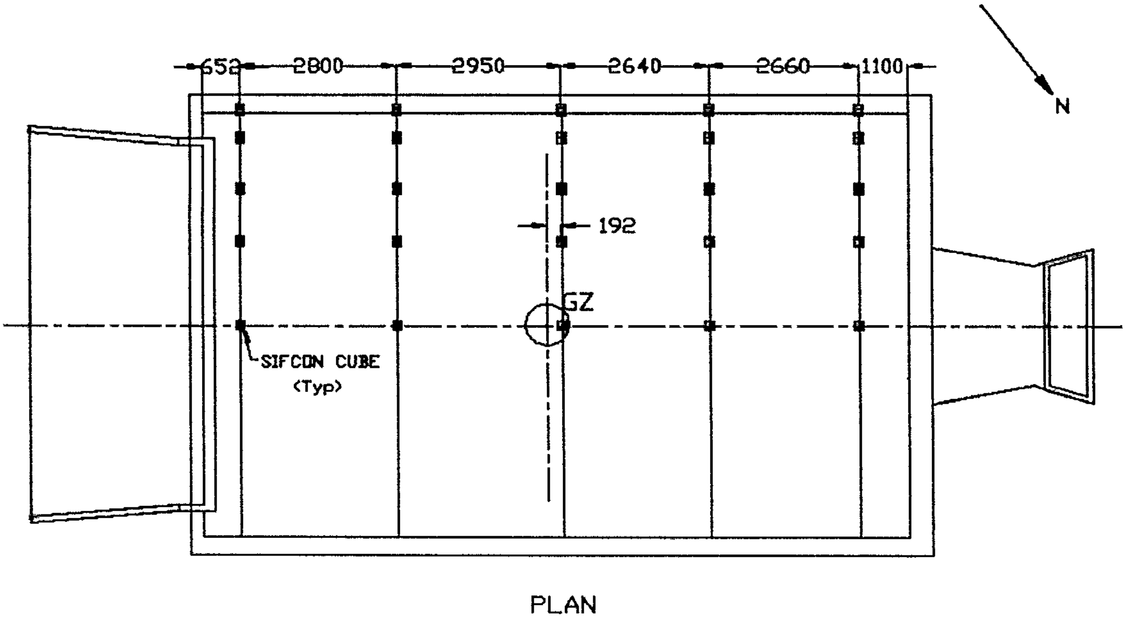

Figure 9: Sifcon Cube Placement Plan View

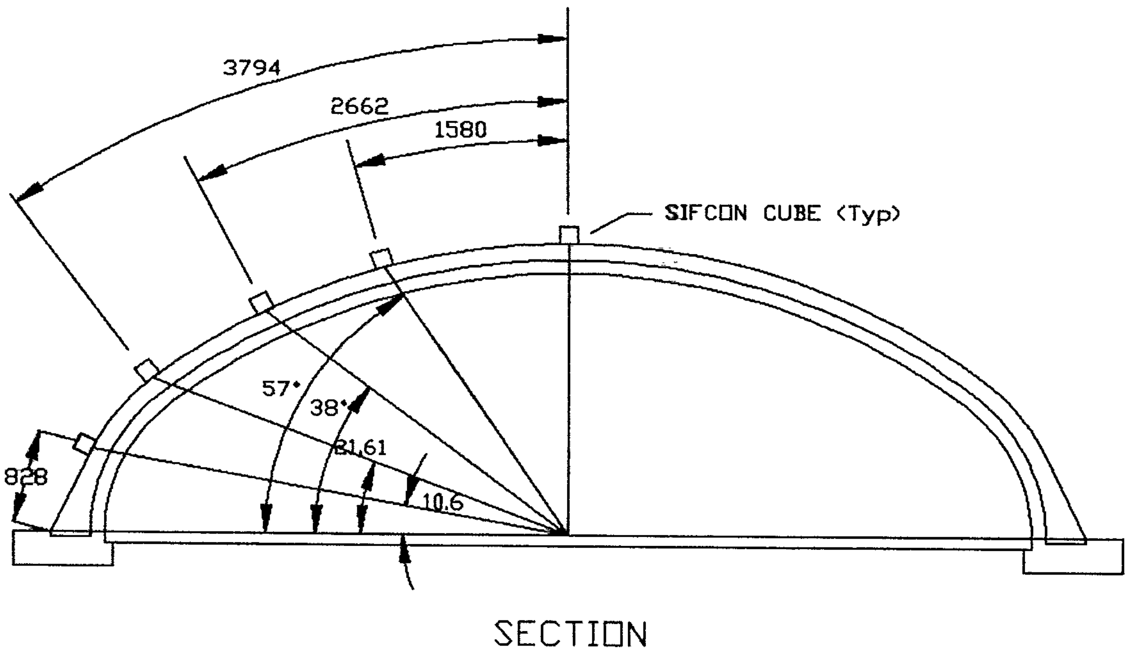

Figure 10: Sifcon Cube Placement Section View

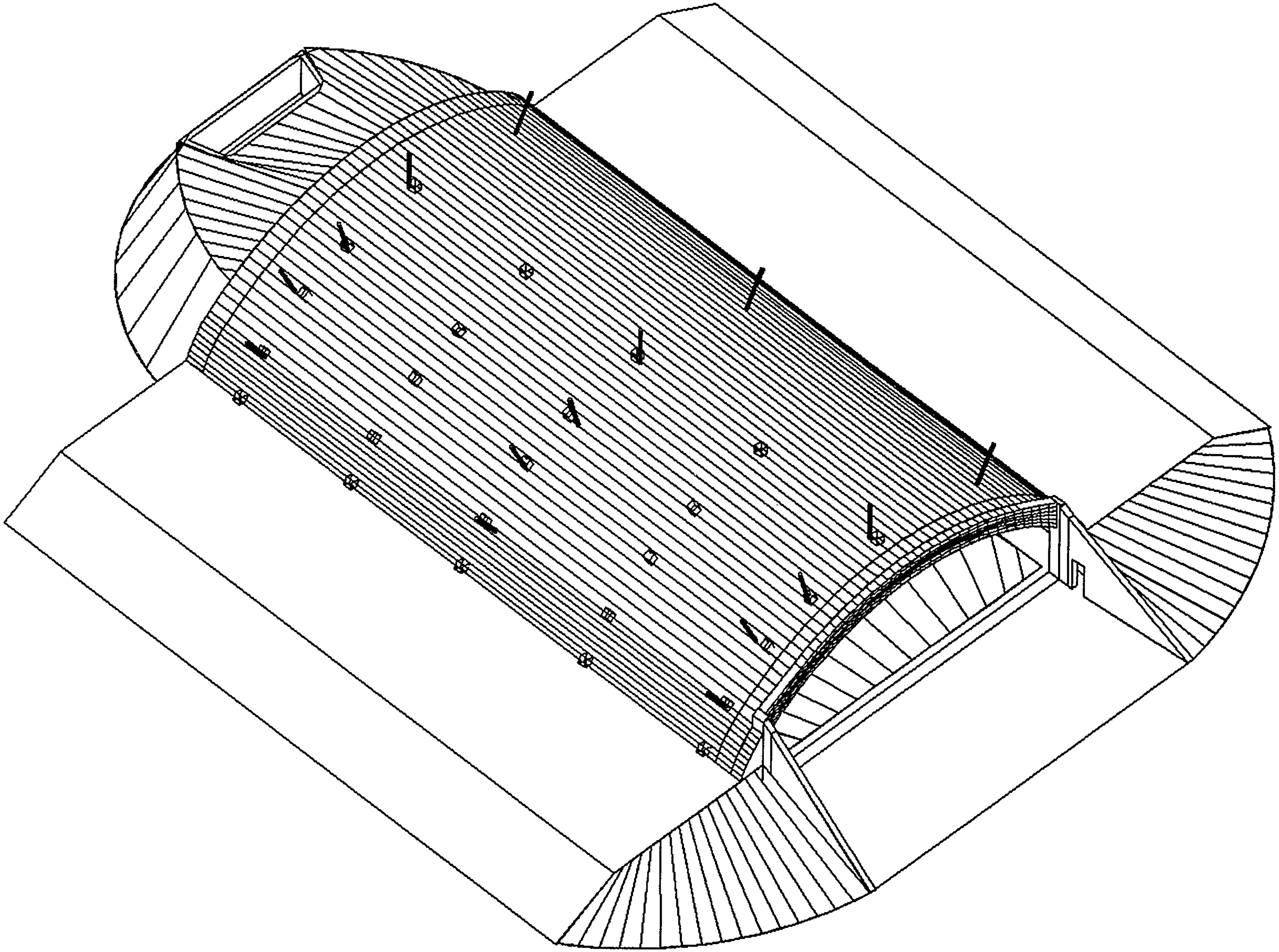

Figure 11: Sifcon Cube Placement Ortho View

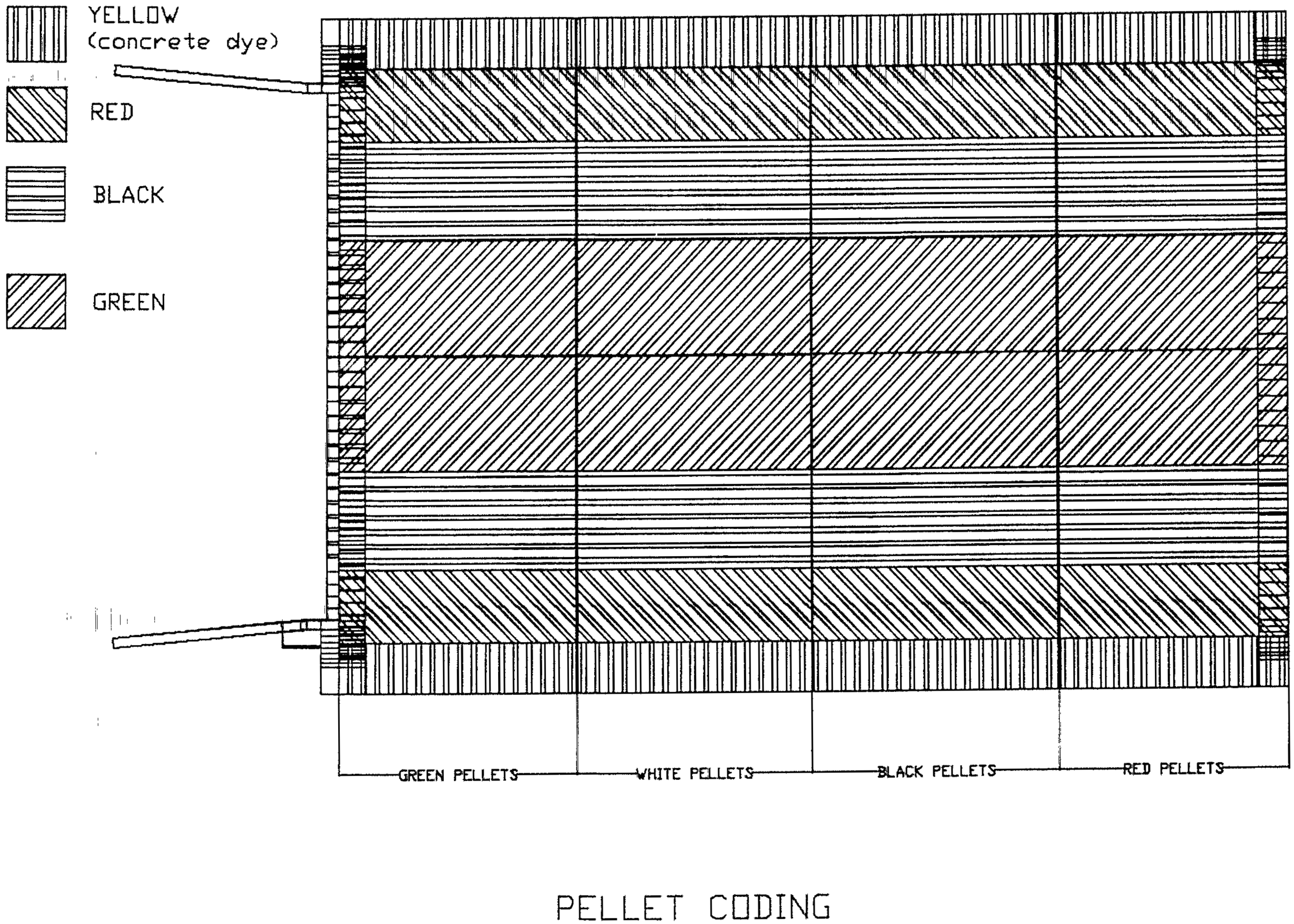

Figure 12: Arch Color Coding

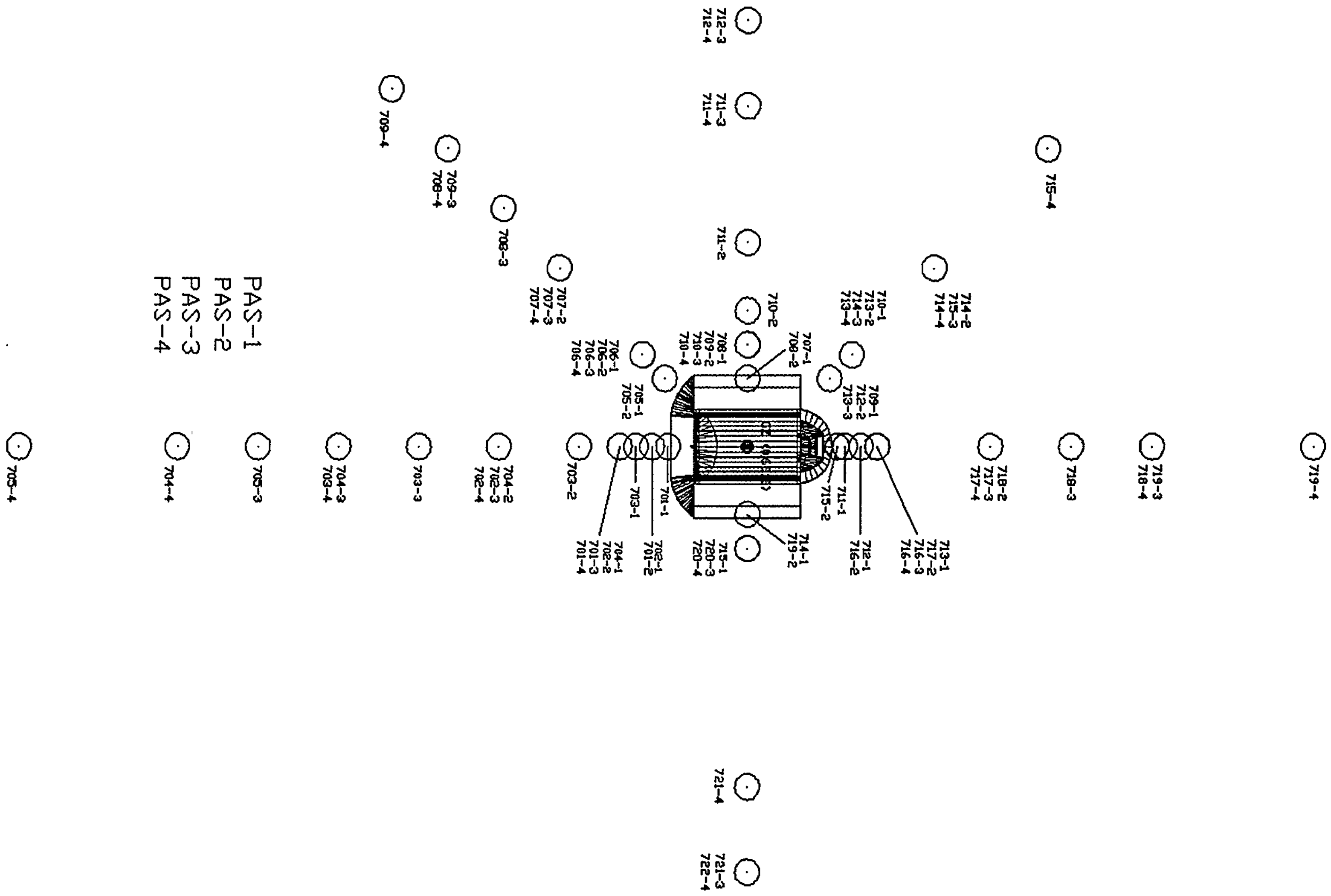

Figure 13: Free Field Gage Map

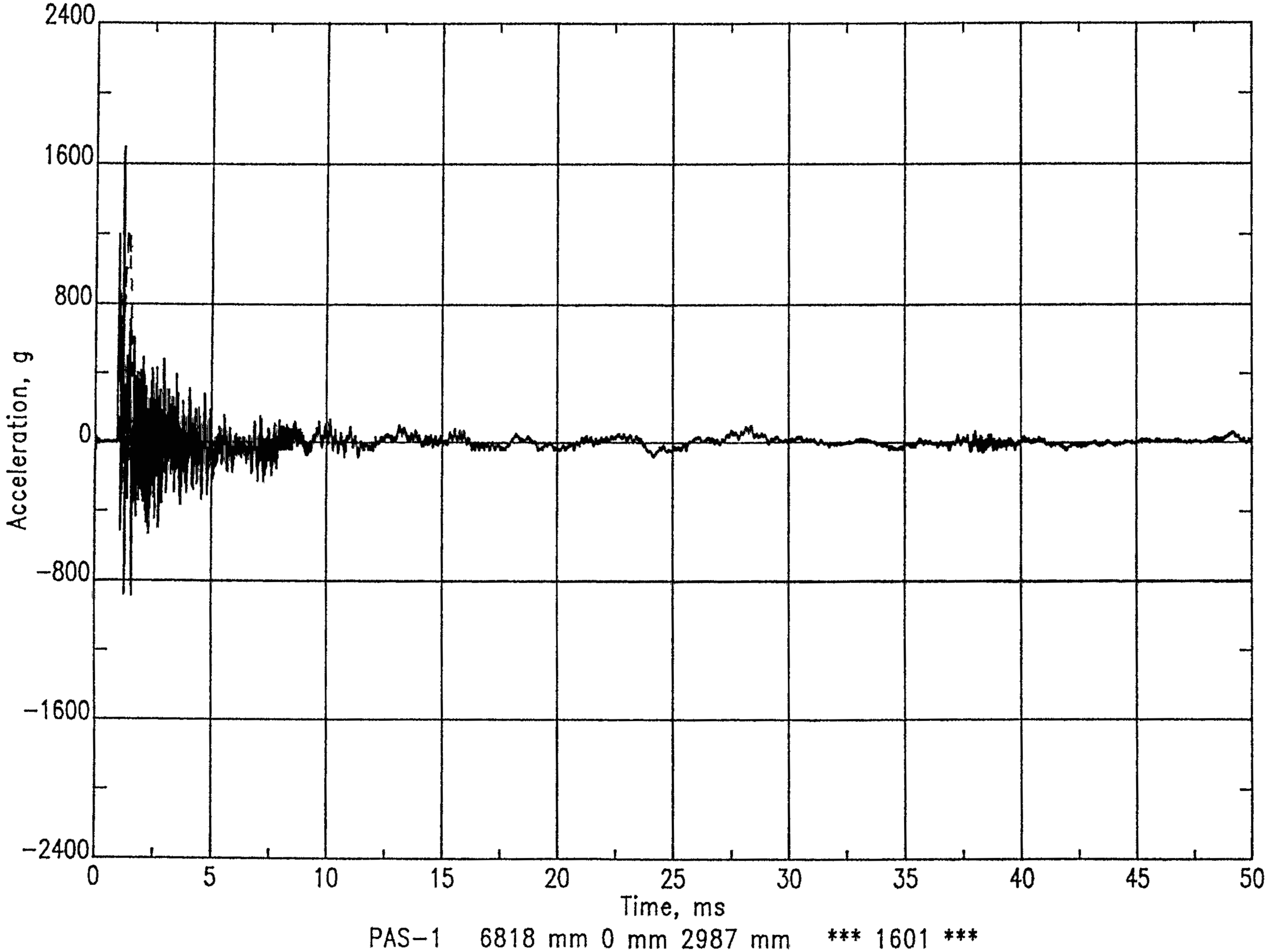

Figure 14: PAS-1 Predicted vs Recorded Accelerations

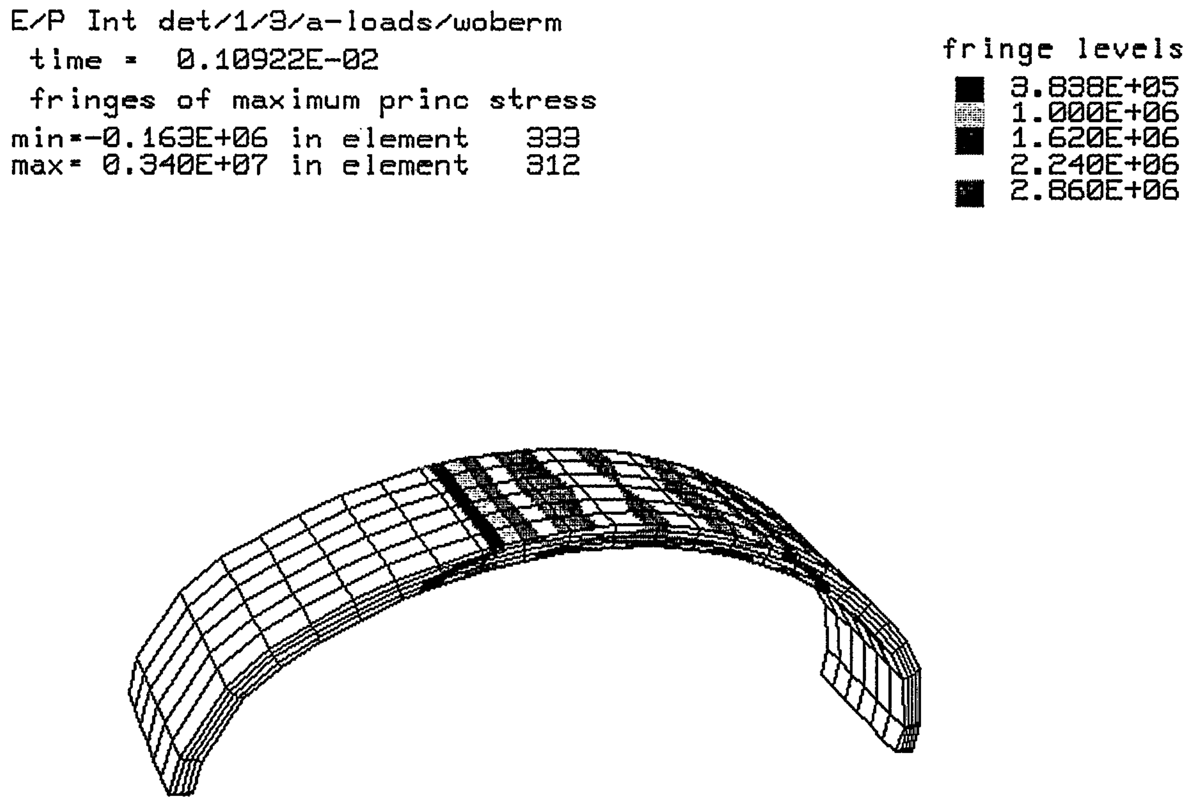

Figure 15: PAS-1 Maximum Principal Stress

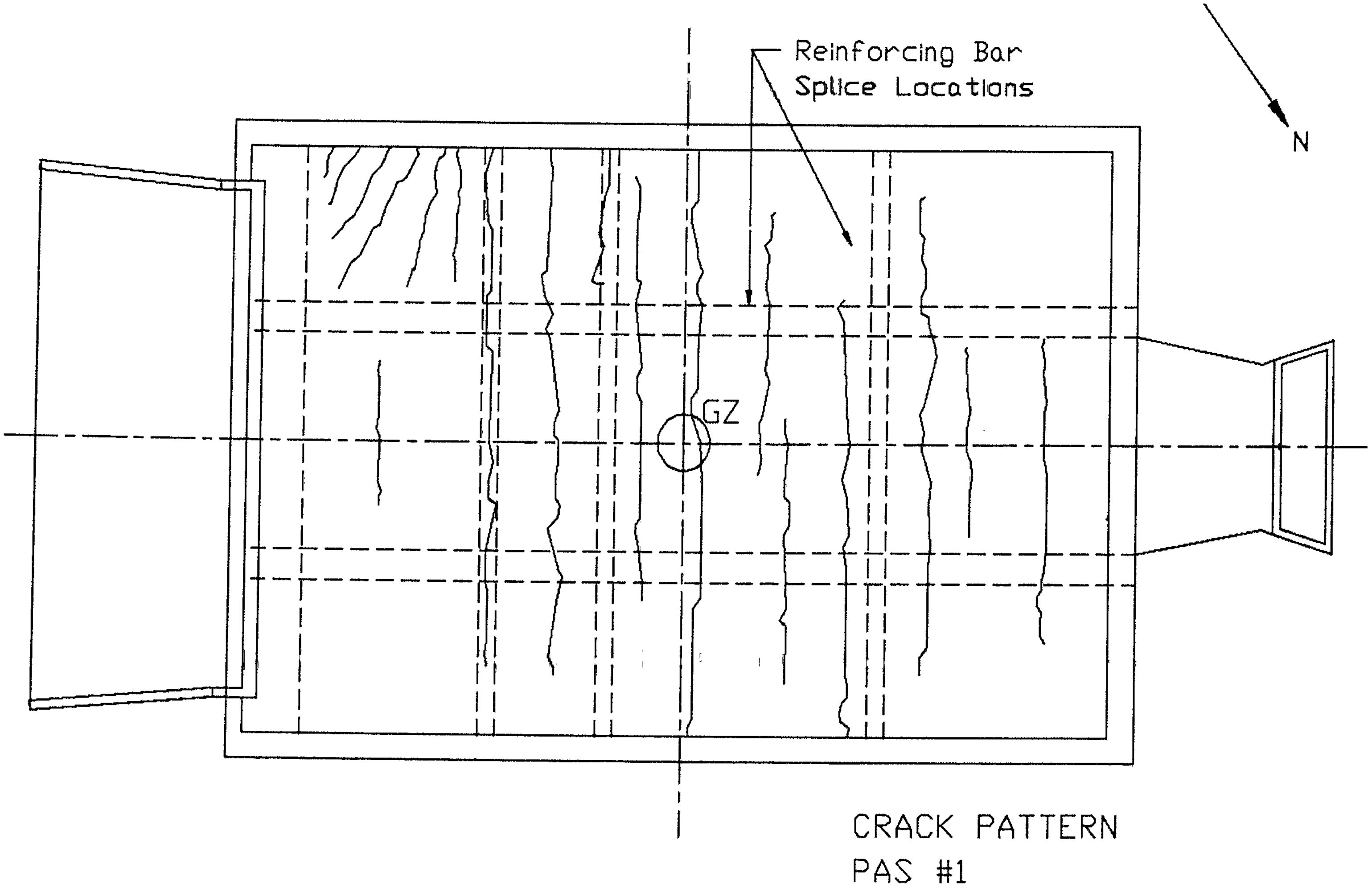

Figure 16: PAS-1 Arch Crack Pattern

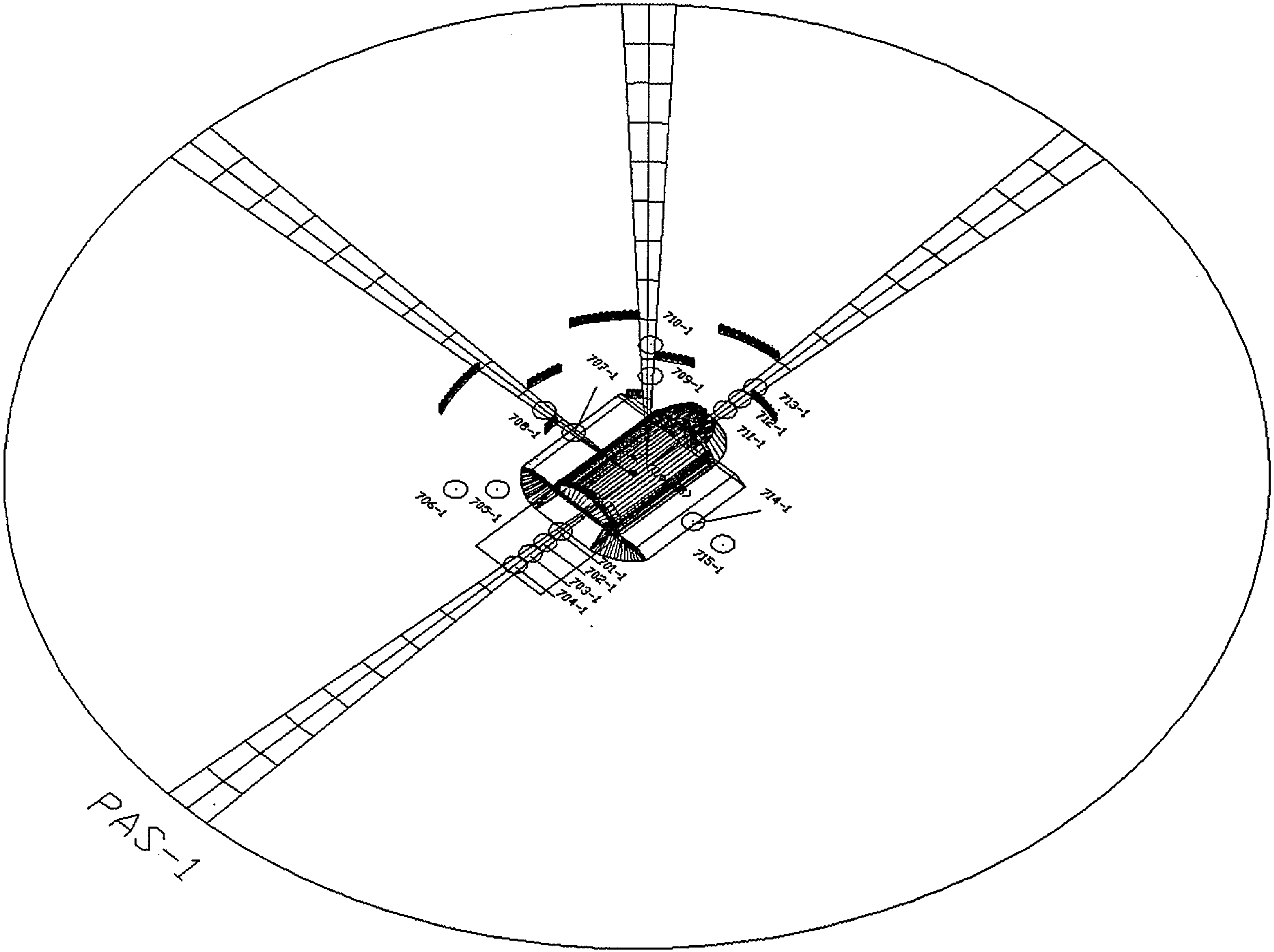

Figure 17: PAS-1 Test Bed Layout

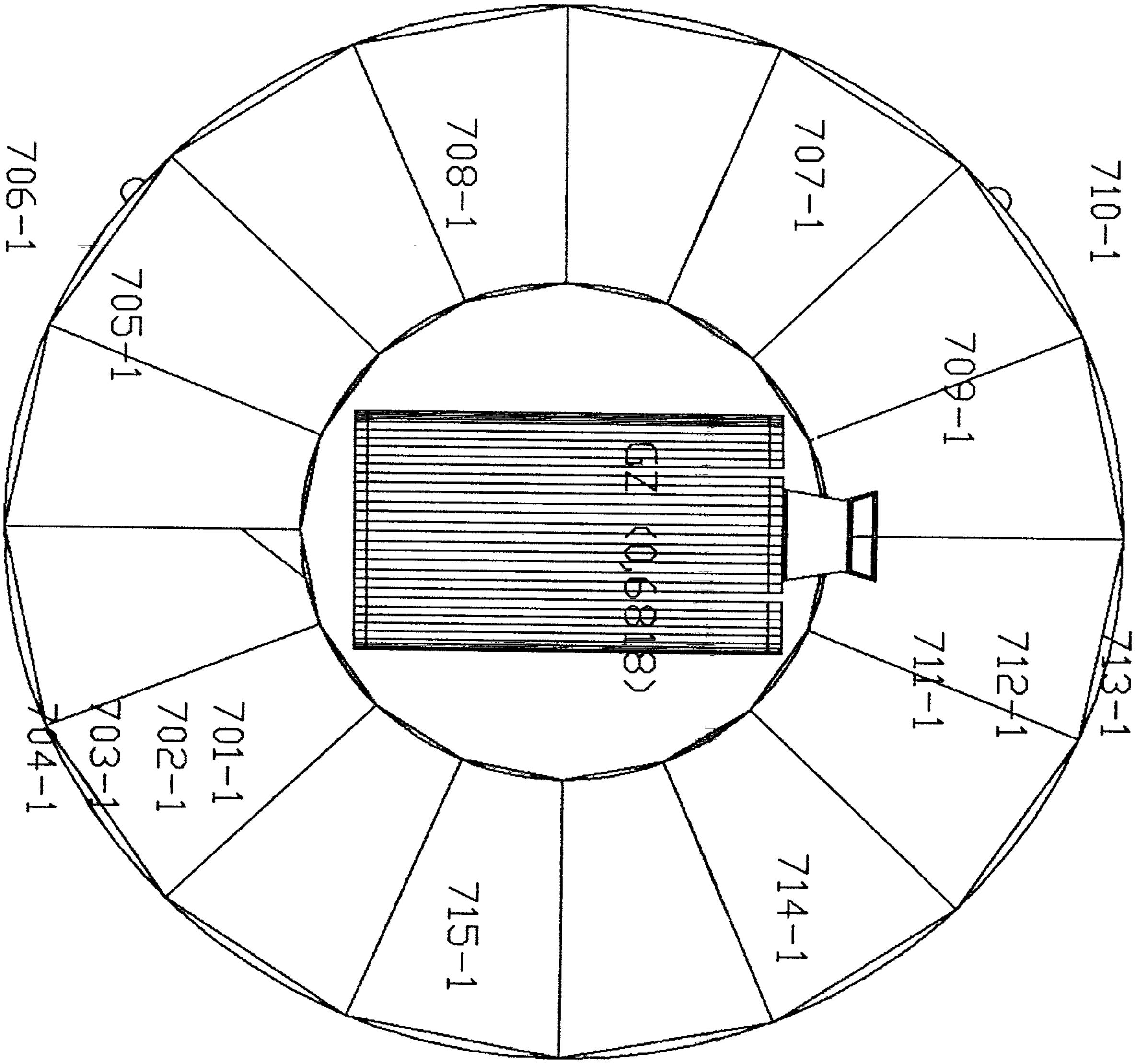

Figure 18: PAS-1 One PSI Contour

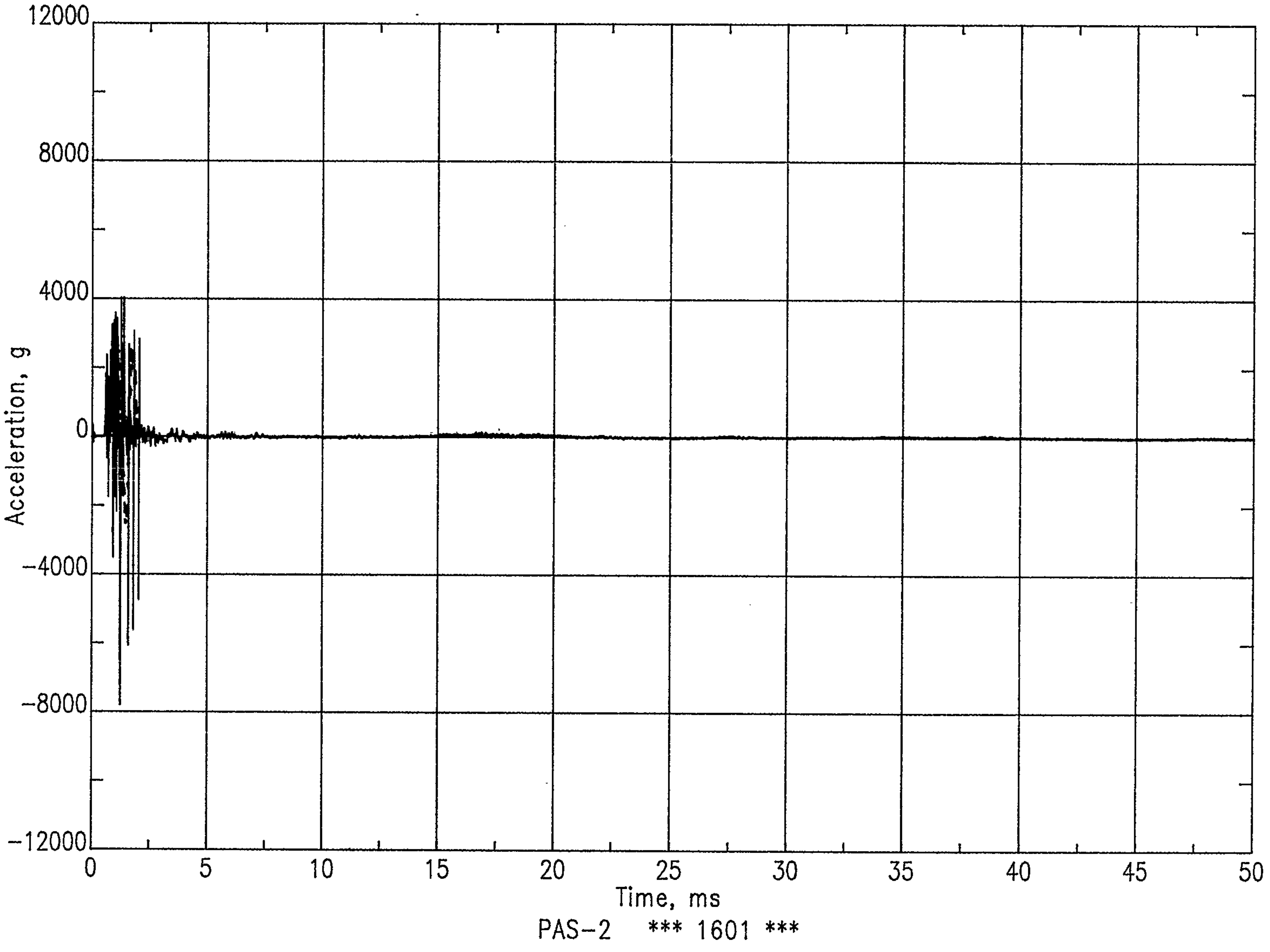

Figure 19: PAS-2 Predicted vs Recorded Accelerations

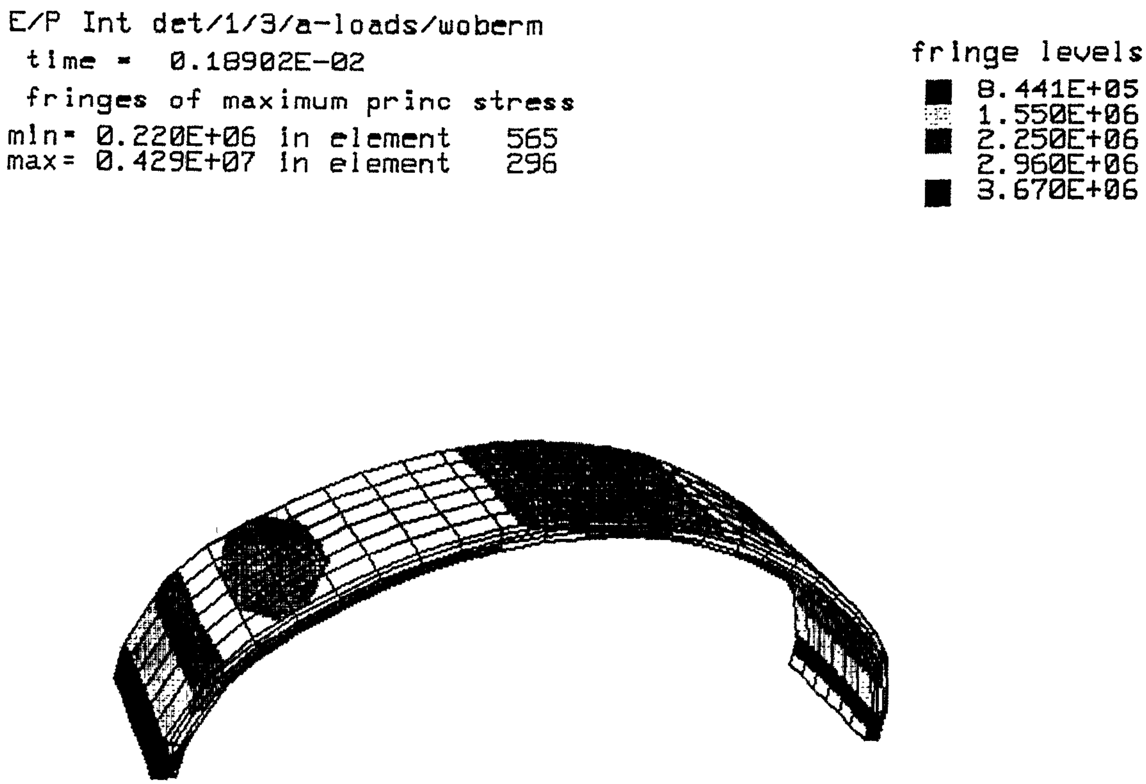

Figure 20: PAS-2 Maximum Principal Stress

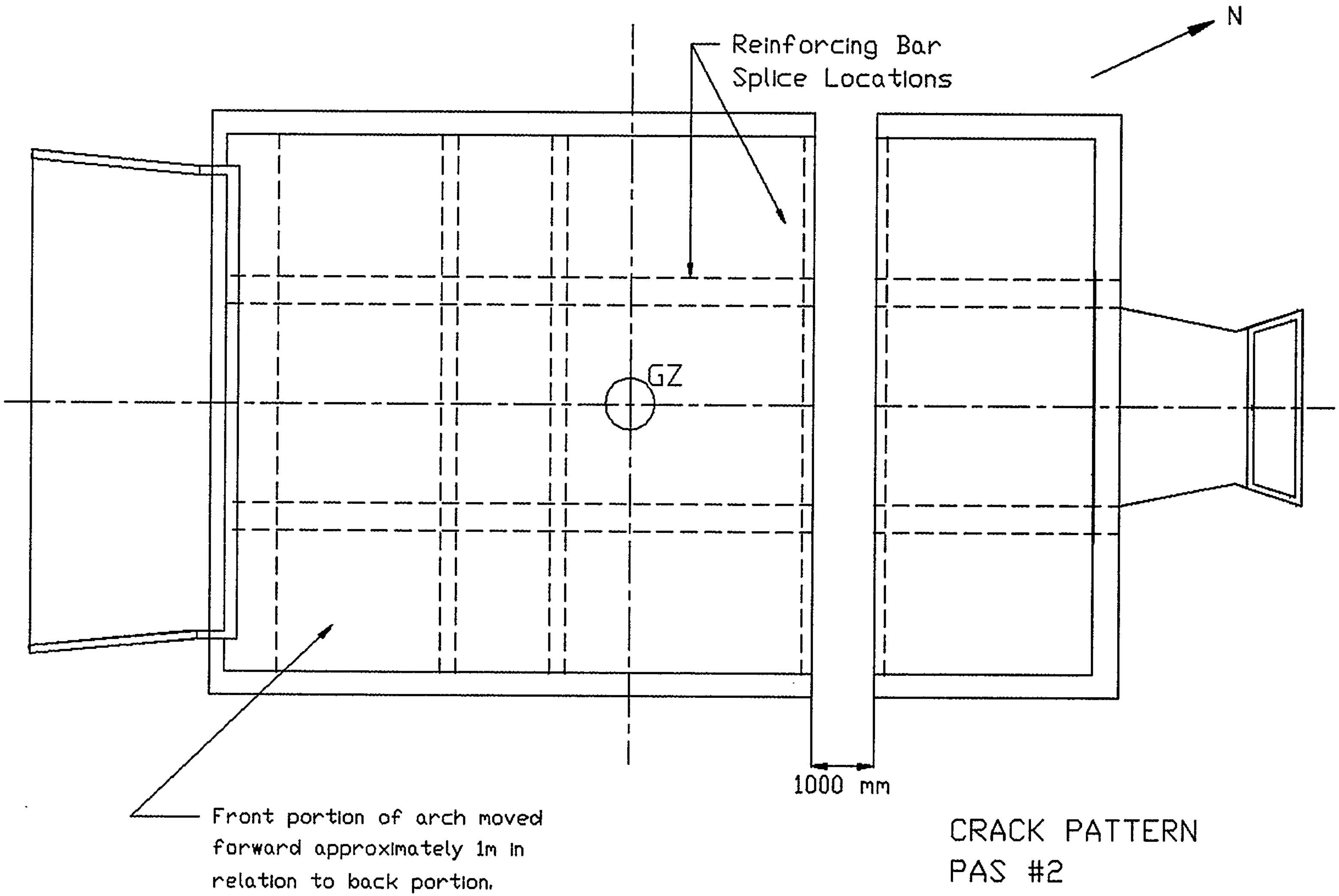

Figure 21: PAS-2 Arch Crack Pattern

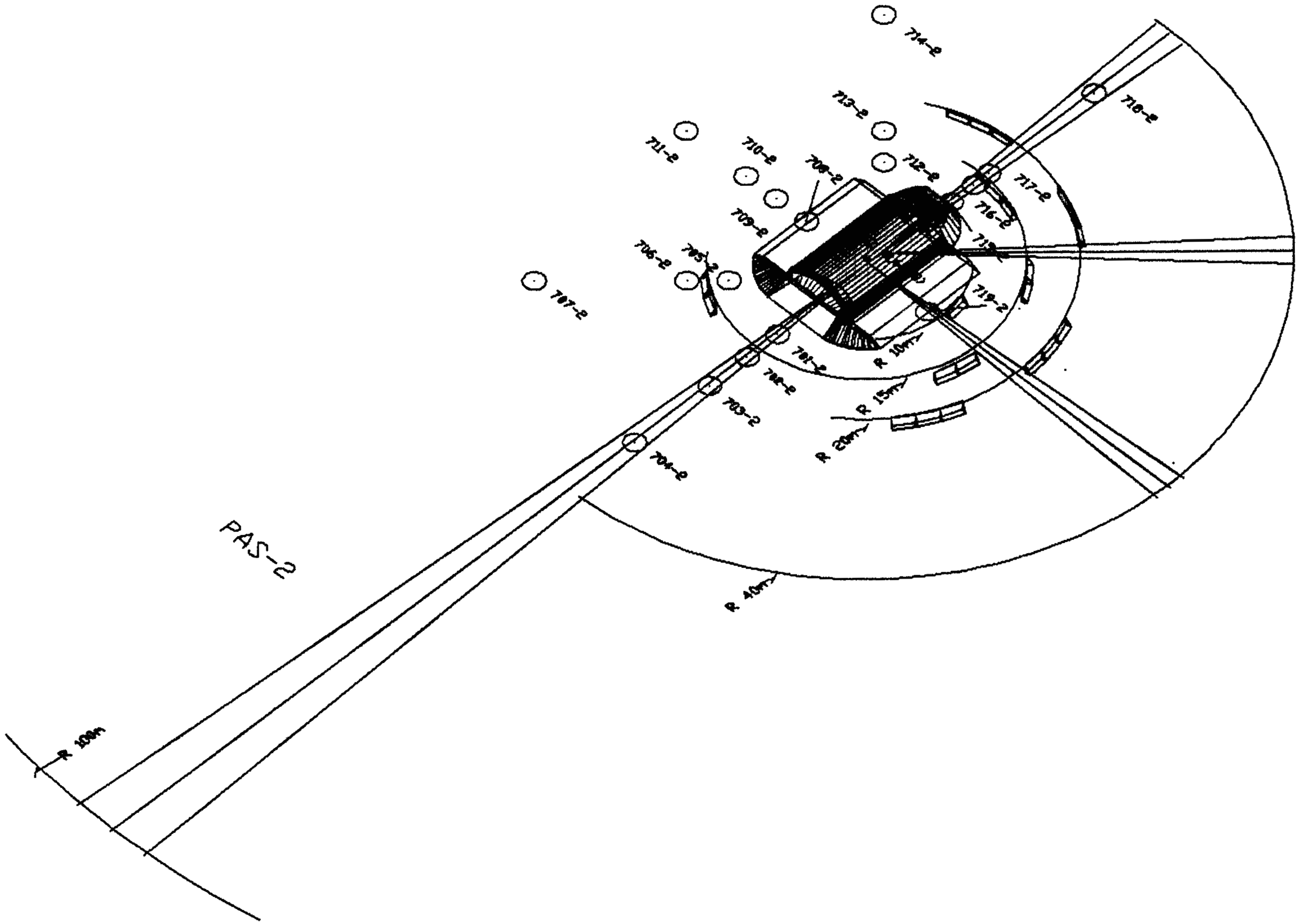

Figure 22: PAS-2 Test Bed Layout

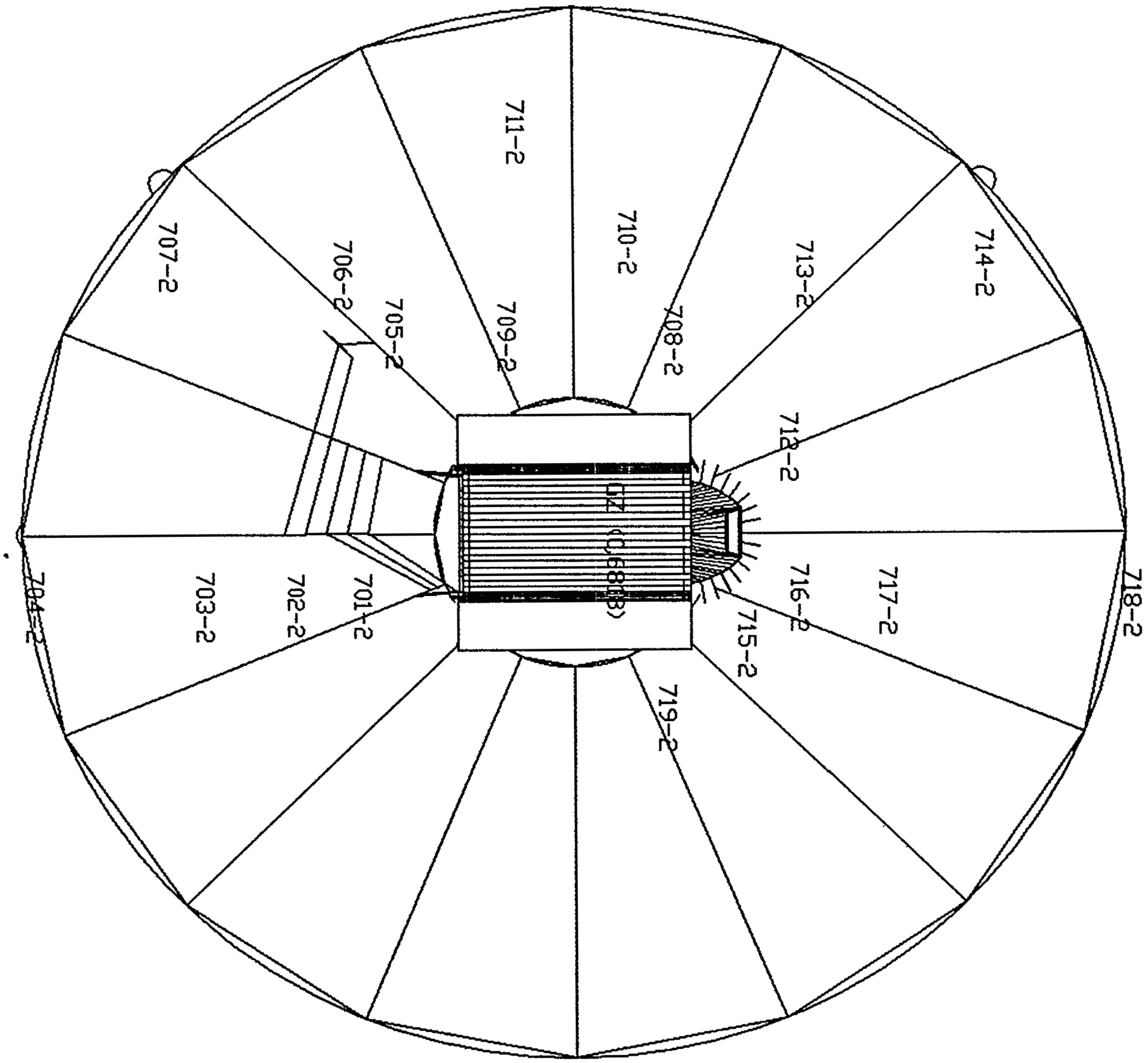

Figure 23: PAS-2 One PSI Contour

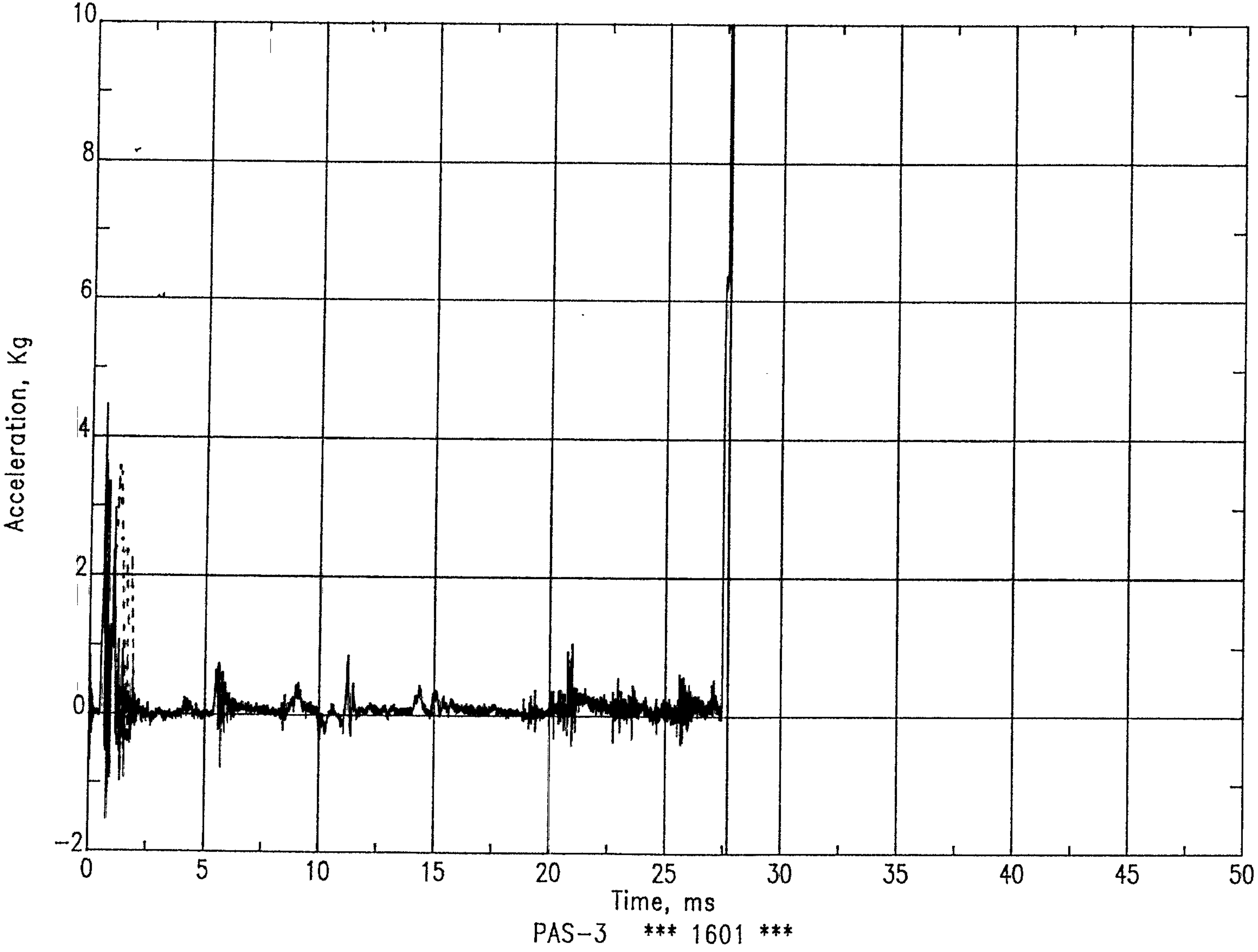

Figure 24: PAS-3 Predicted vs Recorded Accelerations

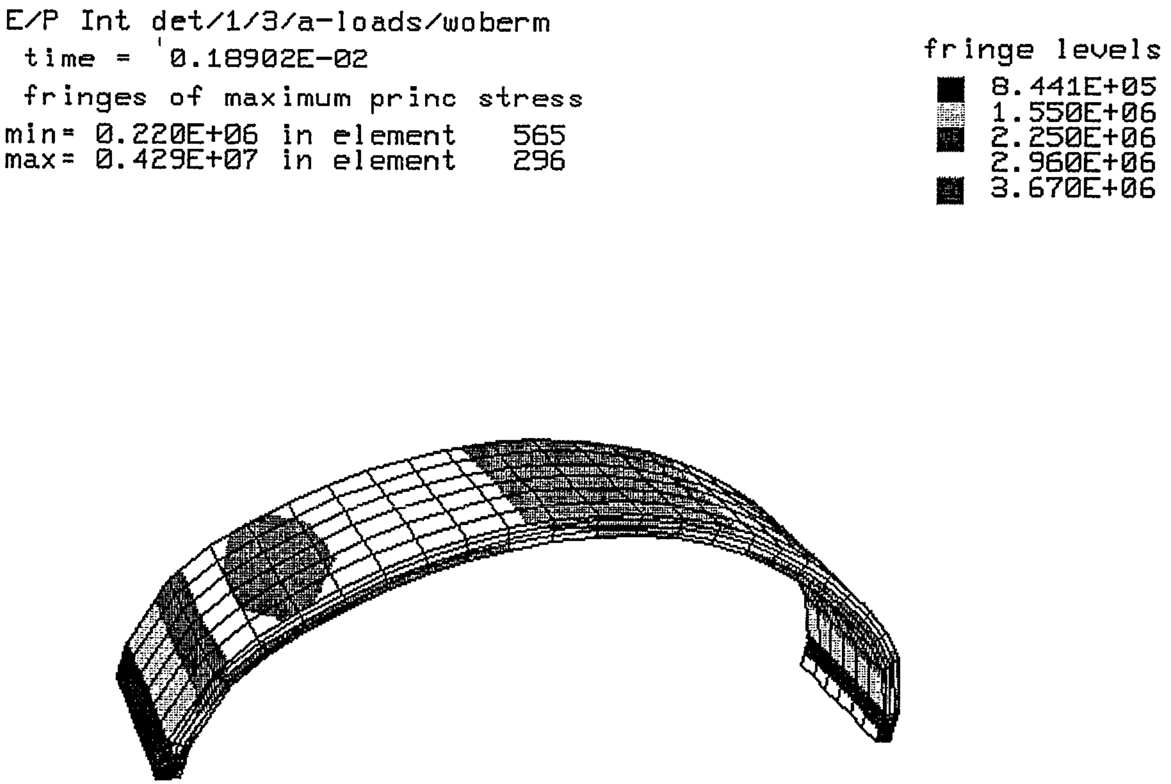

Figure 25: PAS-3 Maximum Principal Stress

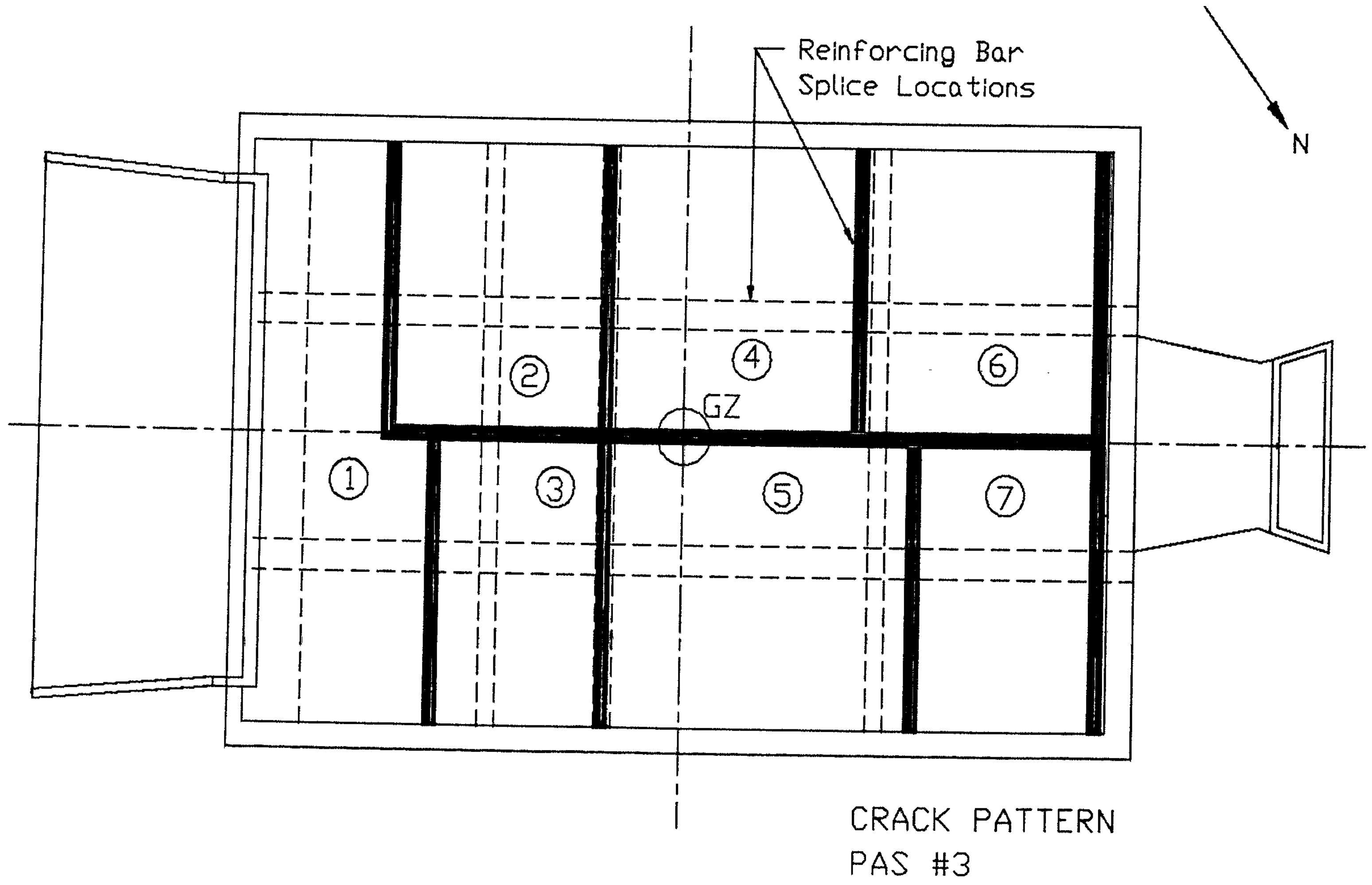

Figure 26: PAS-3 Arch Crack Pattern

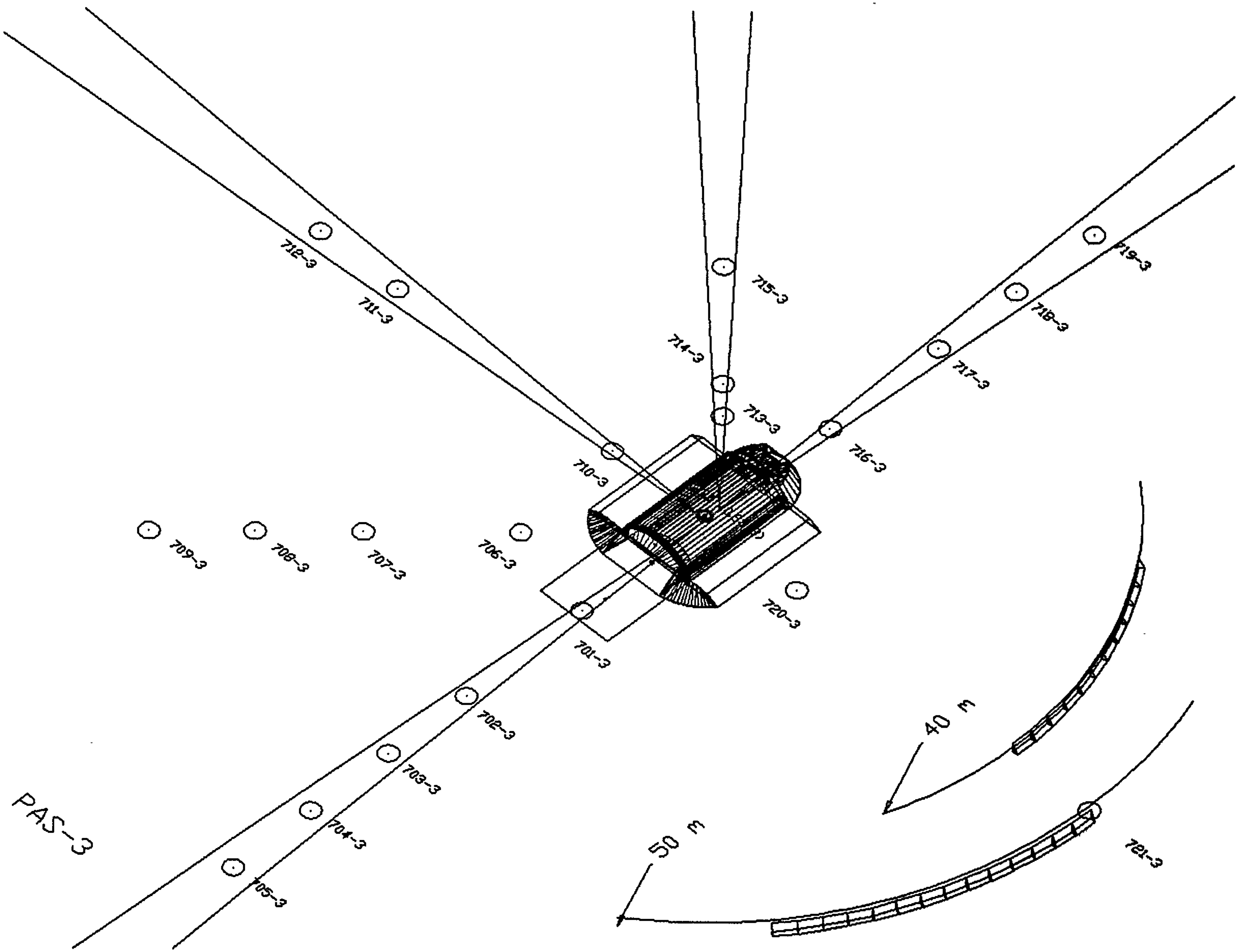

Figure 27: PAS-3 Test Bed Layout

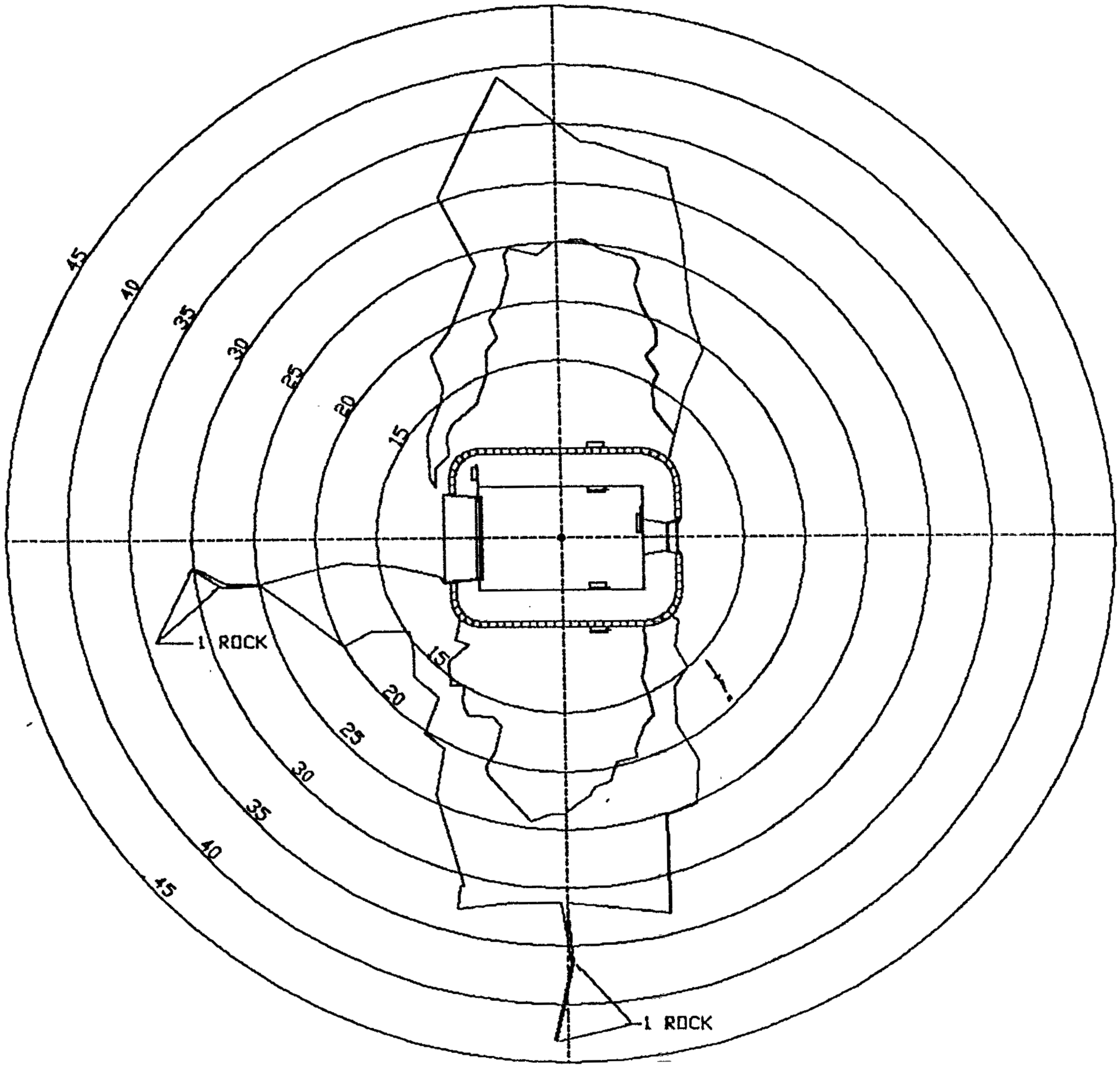

Figure 28: PAS-3 Rock Ruble Distribution Map

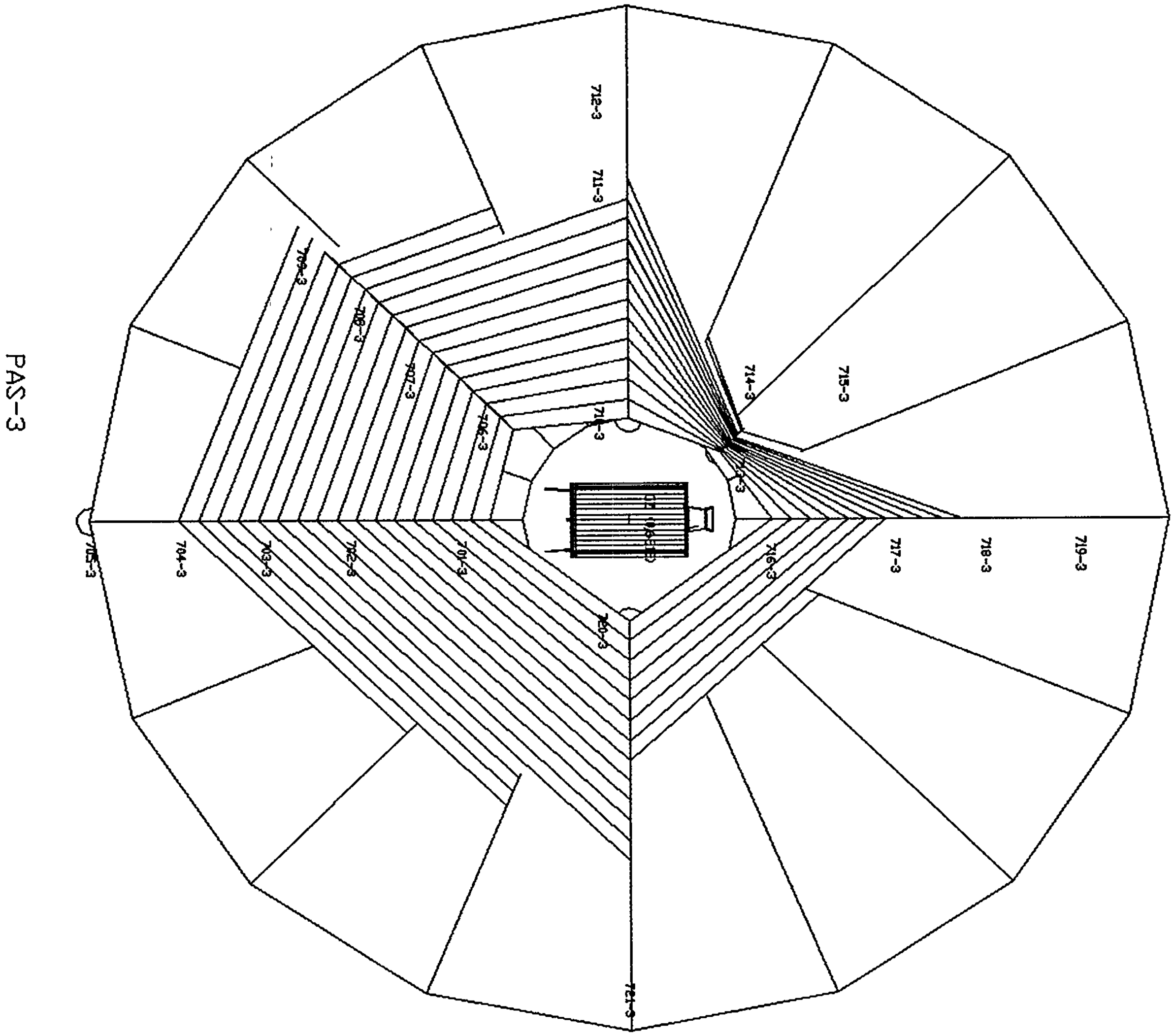

Figure 29: PAS-3 One PSI Contour

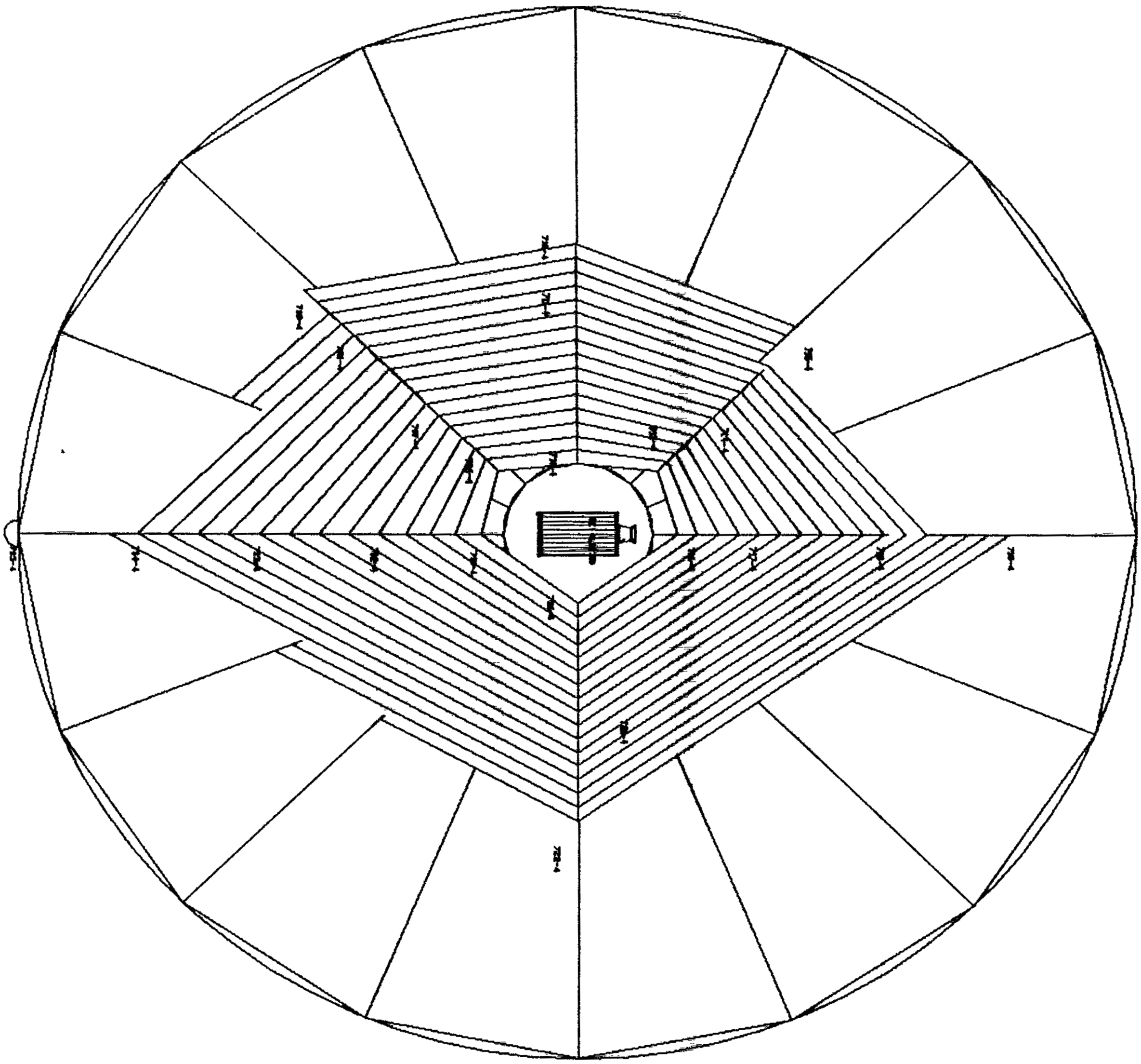

Figure 30: PAS–4 One PSI Contour

Front-Rear Wall Comparisons

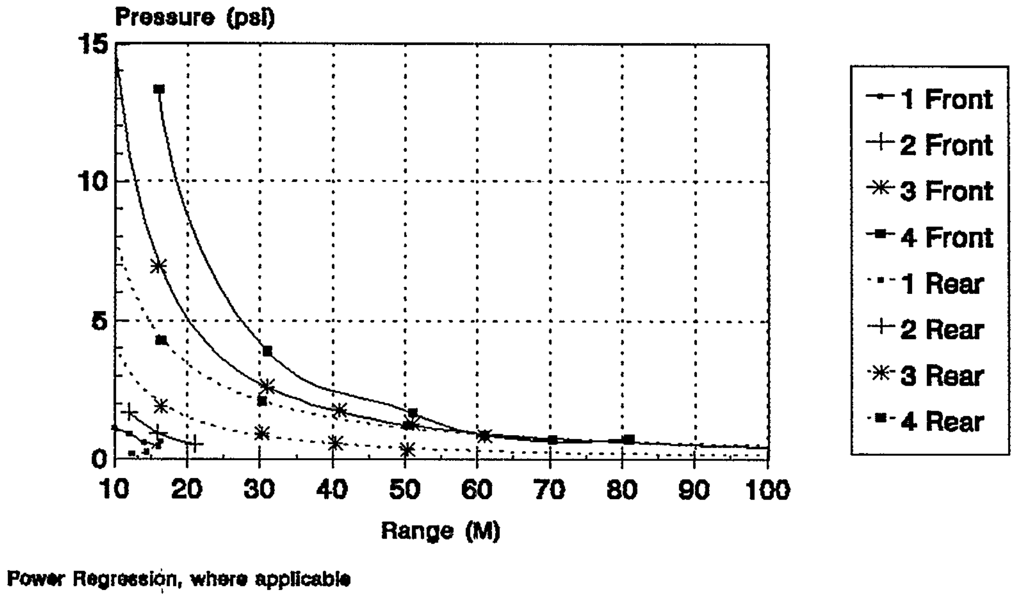

Figure 31: Static Overpressure Front and Rear Wall

Arch Comparisons: North, South

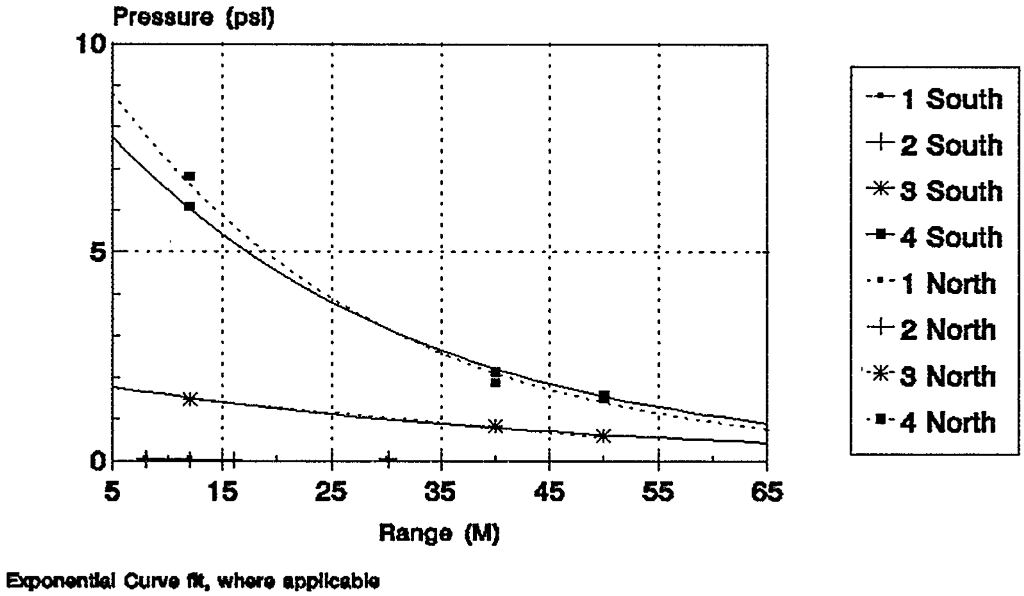

Figure 32: Static Overpressure Arch and 45° Radial